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## **Sensores Acústicos Inteligentes**





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**Sensores Acústicos Inteligentes  
Acoustic Smart Sensors**

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica de José Alberto Gouveia Fonseca, Professor Associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e do Professor Joaquim José de Castro Ferreira, Professor Adjunto da Escola Superior de Tecnologia e Gestão de Águeda da Universidade de Aveiro



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## Resumo

As habitações atuais são incorporadas com uma variedade cada vez mais vasta de sensores e atuadores. Estes sensores, na maioria das situações, tem uma função bastante específica, sensores de gás butano, sensores de gás propano, sensores de monóxido de carbono, sensores piroelétricos. Através da introdução de autonomia a cada um destes sensores, nomeadamente, enviar, processar e receber informação, é possível tornar uma habitação num centro de partilha de informações fulcrais, acessível a partir de qualquer ponto.

Nesta perspetiva, analisando a conjuntura habitacional deduz-se rapidamente que a aplicação de sensores inteligentes não poderá ser feita apenas em novas habitações mas também terá que ser implementada em habitações que já possuem uma rede elétrica implementada. Isto implica desde logo, que este tipo de equipamentos possam ser adaptados a redes que estão em utilização (retrofitting) e que sejam de fácil acesso durante a instalação e manutenção.

Desta forma entram em cena os protocolos de comunicação sem fios. Estes permitem não somente a interligação dos sensores inteligentes (sensor, processador, interface de comunicação), mas também a sua ligação a atuadores e a interfaces pessoa-máquina, sem se pôr a necessidade de alterações físicas às habitações.

A criação de uma solução integradora, utilizando a parede de uma habitação como interface humana é apresentada ao longo deste documento. Este sistema comunica com o gateway de uma casa inteligente utilizando a tecnologia wireless que será estudada e definida como a mais eficiente e segura. Uma vez interligada com o gateway poderá efetuar um conjunto vasto de operações, que estarão definidas no processador da unidade central da casa.

A dissertação aqui apresentada consiste na análise de protocolos de comunicação wireless, e na concepção de um sistema de interface humana embutido nas paredes de edifícios habitacionais.



## Abstract

Nowadays buildings are being progressively integrated with an increasing number of sensors . Most of the times this sensors have quite specific functions, butane sensors, propane sensors, carbon monoxide sensors, pyroelectric motion sensors, and this is what limits their field of action. Introducing a certain level of autonomy to a sensor, *i.e.*, send, process and receiving information can increase the interactivity and market attractiveness of a building.

Within this point of view, and over-viewing the building conjuncture, it can be concluded that smart sensors will be installed during the construction, in recently constructed buildings, but also in buildings with several years which commonly have an physical electric network. This implies that this type of units will need to have an option to be retrofitted and, to a certain degree, a simple installation.

In this thesis, it is proposed the creation of an integrated solution using the wall of a room as a human interface. This system can establish communication with the gateway of a smart home using a previous researched, efficient and safe wireless protocol. Once the connection is established the gateway can execute a large variety of functions that can be programmed in the home central unit (gateway).

The thesis hereby presented consists in a study of wireless communication protocols with respect to reliability, safety and practicality and in the research of the fusion between sensors, processing ability and communication interfaces with the intent of producing a prototype.



# Contents

<b>Contents</b>	<b>i</b>
<b>List of Figures</b>	<b>iii</b>
<b>List of Tables</b>	<b>v</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	3
1.2 Structure . . . . .	4
<b>2 State of the Art</b>	<b>5</b>
2.1 Analysis of Home Automation Technologies . . . . .	6
2.1.1 X10 . . . . .	6
2.1.1.1 X10 Communication Protocol . . . . .	6
2.1.1.2 Advantages and Disadvantages . . . . .	9
2.1.2 HART . . . . .	11
2.1.2.1 Advantages and Disadvantages . . . . .	13
2.1.3 Z-Wave . . . . .	13
2.1.3.1 Network devices . . . . .	14
2.1.3.2 Routing principles . . . . .	15
2.1.3.3 Advantages and Disadvantages . . . . .	15
2.1.4 ZigBee . . . . .	16
2.1.4.1 Advantages and Disadvantages . . . . .	17
2.1.5 Bluetooth and Bluetooth Low Energy . . . . .	17
2.1.5.1 Technology Protocols and Characteristics . . . . .	18
2.1.5.2 Advantages and Disadvantages . . . . .	20
2.1.6 EnOcean . . . . .	21
2.1.6.1 Advantages and Disadvantages . . . . .	22
2.1.7 WirelessHART . . . . .	22

2.1.7.1	Advantages and Disadvantages . . . . .	24
2.2	Technology Overview . . . . .	25
2.2.1	Implementation Size and Market Adoption and Standardization . .	27
2.2.2	Security Protocols . . . . .	27
<b>3</b>	<b>Acoustic Sensing Solution</b>	<b>29</b>
3.1	A Wireless-based Sensing Network in Home Automation . . . . .	29
3.2	Scenario . . . . .	31
3.3	Architecture Block Diagram . . . . .	33
3.4	Implementation . . . . .	35
3.4.1	Microcontroller . . . . .	35
3.4.1.1	Arduino and ATmega328P . . . . .	35
3.4.1.2	Integrate Development Environment (IDE) . . . . .	36
3.4.1.3	Energy Consumption . . . . .	36
3.4.1.4	Interfaces with external devices . . . . .	36
3.4.2	Communication . . . . .	38
3.4.2.1	Approach to BLE 4.0 communication . . . . .	38
<b>4</b>	<b>Results</b>	<b>49</b>
4.1	Sensing . . . . .	49
4.1.0.1	Microphone . . . . .	50
4.1.0.2	Piezoelectric Module . . . . .	53
4.2	Performance . . . . .	57
4.2.1	Latency . . . . .	57
4.2.2	Sensor Unit Wall Area Coverage . . . . .	59
4.2.3	Network of Smart Sensor Units . . . . .	63
<b>5</b>	<b>Conclusions</b>	<b>67</b>
5.1	Critic Analysis . . . . .	69
5.1.1	Knock Filtering . . . . .	69
5.1.2	Knock Positioning . . . . .	69
5.1.3	Knocking Combinations, Codes and Alternative Gestures . . . . .	70
5.2	Future Work . . . . .	71
	<b>Bibliography</b>	<b>73</b>
	<b>Appendices</b>	<b>77</b>
<b>A</b>		<b>78</b>

# List of Figures

2.1	X10 based home automation units (extracted [12]). . . . .	6
2.2	X10 based home automation units. . . . .	7
2.3	X10 House Code. . . . .	8
2.4	X10 House Letter Attribution. . . . .	8
2.5	X10 Number Code. . . . .	8
2.6	X10 Number Attribution. . . . .	8
2.7	X10 Number Attribution (extracted [12]). . . . .	9
2.8	HART Frequency Shift Keying (adapted[35]). . . . .	11
2.9	Two communication channels, Point-to-Point topology adapted[30]. . . . .	12
2.10	Multidrop communication(adapted[30]. . . . .	12
2.11	Z-Wave units (extracted [13]). . . . .	13
2.12	Z-Wave Protocol Structure (adapted [13]). . . . .	14
2.13	ZigBee Protocol Structure (adapted [18]). . . . .	16
2.14	Advertising and Scan Response Example.(adapted[24]). . . . .	19
2.15	Connection interval Example.(adapted [24]). . . . .	20
2.16	EnOcean based Neptronic products. (extracted [33]). . . . .	21
2.17	WirelessHART protocol stack.(adapted [22]). . . . .	23
3.1	Application Example of the new proposal (SSU- Smart Sensor Unit). . . . .	30
3.2	House Network with multiple Smart Sensor Units. . . . .	32
3.3	Block Diagram of the Proposed Architecture. . . . .	33
3.4	ATMega328P microprocessor (extracted[23]). . . . .	37
3.5	Arduino state diagram. . . . .	37
3.6	The HM-10 breakout board (extracted [43]). . . . .	39
3.7	CC41A Breakout Board Schematic (extacted [43]). . . . .	39
3.8	HM-10 modules function. . . . .	40
3.9	Role and name configuration on the HM-10 modules. . . . .	41
3.10	Working diagram of the peripheral unit. . . . .	44

3.11	Master's flowchart. . . . .	45
3.12	Structure of the advertising and connect process. Two phases, (1) and (2). . . . .	46
3.13	Diagram of the knocking and following events. . . . .	46
3.14	Time graphic of the knocking and following events. . . . .	47
3.15	Network and Communication Links. . . . .	48
4.1	Areas of actuation of two sensor units on the same wall. . . . .	49
4.2	Circuit of the sound sensor module. Units: 104-0.1 $\mu$ F. (adapted [41]). . . . .	50
4.3	Electret Microphone [44]. . . . .	51
4.4	Experiment representation. . . . .	51
4.5	Sound detection module (adapted [41]). . . . .	53
4.6	Piezo Disk Vibration Sensor Schematic (adapted [25]). . . . .	54
4.7	Piezo Disk Vibration Sensor Used (adapted [25]). . . . .	55
4.8	AT+INQ? command response during tests. . . . .	57
4.9	First experiment results by colour. . . . .	59
4.10	Second experiment results by colour. . . . .	60
4.11	Smart Sensing Unit. . . . .	62
4.12	Gateway Simulator (Central). . . . .	62
4.13	Bluetooth based Network applied in the implementation. . . . .	63
4.14	Bluetooth based Network applied to an extensive implementation. . . . .	65
5.1	Distance from knock to each sensor, example of triangulation. . . . .	70
A.1	Knock frequency analysis (Spectrum Analyzer, academo.org). . . . .	78



# List of Tables

2.1	X10 function list. . . . .	10
2.2	The Confrontation between Wired vs Wireless . . . . .	25
2.3	Confrontation between the different researched technologies . . . . .	26
3.1	List of AT Commands used with the HM-10 BLE modules (adapted: [43]).	42
4.1	Knocking Tests Experiment Result (ID - Incorrect Detection, ND - No De- tection, D - Detection) . . . . .	52
4.2	Results of the vibration detections on 3 types of wall. . . . .	56
4.3	Numeric results of the first experiment. . . . .	59
4.4	Numeric results of the second experiment. . . . .	60



# Chapter 1

## Introduction

The incorporation of electronics, informatics and telematics in residential buildings, "Domus" in Latin, gave birth to the word "domotics" [4]. Residential buildings are a primary way of improving human quality of life considering that they are where we spent a great part of our life. The presence of electric devices in residential buildings increases by the year, at the same rate the embedded electronics are improving their efficiency. The vision of a network where every physical object possesses the ability to collect and exchange data via wireless communications (Internet) is named Internet of Things (IoT).

IoT is getting wide attention from the industrial and academic environments, the idea of an everyday artifact equipped with sensing, communication and processing power, is an exciting prospect for the future [3]. Within the range of IoT in residential buildings the most suited definition of domotics is:

*"...the mechanism of removing as much human interaction as technically possible and desirable in various domestic processes, and replacing it with programmed electronic systems."* [5]

The beginnings of domotics goes back to the appearance of electrical/mechanical wiring in homes. A few of the first steps in the direction of modern domotics were:

- Mechanical and electrical systems to call house maids and door bells (1600-now).
- Distribution of steam in large cities such as New York City in the end of the 19th century.
- Distribution of gas/liquid gas in order to end the necessity of manual refueling on heating systems.

- Set back thermostats and mechanical counters.
- Distribution of electricity in buildings and the development of the first every day appliances.

These topics show that even on a rudimentary level, home automation (domotics) is around us a long time ago and is gradually being embedded in buildings.

In the late 1970's, X10 protocol was presented to the world by Pico Electronics in Scotland. The company was the first to manufacture a line of products only intended for home automation. Since then, another companies and technologies have emerged, the study on the technologies is presented with more detail in the state of the art chapter. These primordial systems comprised a series of sensors and actuators that were connected to a main central processing unit. These systems had very high manufacturing costs, high end-user cost and they were not embeddable in existing systems [8].

The progress made in the science of electronics during the following years did not only exponentially increased the processing power available (as predicted in Moore's law) but also decreased the costs of the hardware (lower implementation sizes, higher production volume). The distribution of the controlling system (DCS) turned reality, *i.e.*, the control is not made at a single processing unit but instead it is distributed in an hierarchized network, and this actually improved the life expectancy of the equipment, flexibility and new equipment integration.

The main advantages when implementing home automation systems are:

- **Safety:**  
Information from security cameras, door locks and motion sensors available remotely allow real time and constant monitoring.
- **Convenience:**  
Ending physical effort in activities such as window covering, door opening and light switching turns a home a much more comfortable and enjoyable space.
- **Economy:**  
The external access to a gateway that allows the user to turn off lights but also, for example, close windows and doors (temperature management) can have a significant impact in the electric bill and environmental footprint.

The disadvantages are mainly:

- **High costs of the products comparing to traditional alternatives:**  
The implementation of sensing units in certain spots and their integration with the

network of a factory plant can instantly increase the productivity and this, in a short term, results in the return of the investment made. In the residential world is not that simple, even though an overvaluation for buildings implemented with such devices is experienced, the return of the investment will not be so pronounced financially as it is on the excellency of the home interaction.

- **Requirement of a high skilled maintenance team:**

Devices are much more complex than the common switches and power outlets. Mal-function causes can't be evaluated as quickly and device replacement might be necessary.

- **Privacy and security:**

With the remote access to critical operations in residential buildings for example, a owner might be able to, via internet, unlock a door in the residence, at the same time the sharing of such control tasks adds risk to the system.

The interaction with the building functions is nowadays restricted to switches and touch screens. This thesis will explore an alternative to both these systems and make the entire wall area accessible as a switch. The user will not need to change the switch, a simple knock on any part of the wall will start a chain of actions that ends when the desired task is completed.

## 1.1 Motivation

The thesis author shares an interest in the incorporation of state of the art technology in architecture projects. This lead to an eagerness in understanding what technologies are present in residential buildings. From the analysis of the extincted and existing technologies and their individual characteristics, emerged the idea to create something different and innovative.

Other aspects that could not be overlooked and are prevalent in most global summits, are the serious concerns about the world energy resources. With every single one of us becoming increasingly conscious of the environmental issues of energy wasting, the number one reason that make consumers acquire a Home Automation System is Energy Saving [6] [7]. Simultaneously there are studies that demonstrate how “the home automation market is in the high growth stage of the industry life cycle”. Home automation industry was worth in the year 2010 2.9 billion euros, in 2013 5.24 billion euro and recent studies show that (according to a annual growth rate, of 10-11%) it will be worth 11.63 billion euros by

2020. Insights show that in Europe only, by 2017, 36 million homes will be smart [2].

This thesis endeavors in the uncovering of some of the technologies that are considered by the author as the more relevant in both the existent industry and in the process of Home Automation evolution. Further in this thesis an electronic smart device is implemented as a home automation solution.

## 1.2 Structure

This thesis is divided into 4 chapters which are briefly described.

Along the second chapter is presented the background information on the home automation protocols and relevant advantages and disadvantages of each technology. A distinction is made between wired and wireless implementations from the point of view of each other benefits and limitations when applied in different fields.

On chapter 3, a new solution for the domotics field is proposed, a new way of user interfacing with buildings. A discussion of the challenges of the new solution follows. A description of the used materials and their specific characteristics in the scope of the solution proposal is made. Finally it is described the development and implementation of a single sensor unit and then a network of smart sensor units, simultaneously with their communication with a central unit.

Chapter 4 presents results and analysis of the experiments and performance tests made to the implemented system.

The fifth and last chapter sets the conclusion of this thesis and identify diverse paths for future work.

# Chapter 2

## State of the Art

The fast progress of technology and the evident thriving of the first home automation systems resulted in a lot of enterprises starting to dedicate more resources to this area.

As a result we have now a large variety of protocols, services and products available. In the development and engineering of home automation systems, similarly to other systems, having a clear and coherent idea of the existing technologies and their advantages and disadvantages is fundamental. A low energy mentality is being progressively adopted in the design of nearly every electronic device and is opening a new field in the creation of integrated solutions that combine several electronic circuits and can still be powered for several months with the charge of a single coin battery.

This chapter elaborates the most relevant technologies.

## 2.1 Analysis of Home Automation Technologies

### 2.1.1 X10



Figure 2.1: X10 based home automation units (extracted [12]).

In the late 1970's a company named Pico Electronics Ltd., based on Scotland, starts the development of a system which consisted on sending modulated bursts of radiofrequency into the electric grid of a domestic home working at 110VAC or 220VAC.

Later Pico Electronics Ltd. merged with BSR (X10 Ltd), where the product evolved from simple lamp controllers to wall switches and the X10 timer.

In the middle 90's BSR closed, but X10 based products kept being developed by other companies of the area.

The X10 systems consist of 3 main types of devices: emitters, receivers and transceivers (receive and re-transmit RF data). These devices are powered by transforming the voltage available at power outlets 220V or 110V into 5V, which is a highly used voltage in today electronics.

#### 2.1.1.1 X10 Communication Protocol

The X10 communication is made by sending temporary bursts of 120 kHz onto the electric powerline at the zero crossing of the sine wave. As bursts spread throughout the powerline,



*i.e.*, the bursts are broadcasted, every X10 connector in the grid will be able to access them. The solution found by the developing engineers to solve this problem was to attribute every connector with its own code.

The full transmission of the code uses 11 cycles of the 50Hz powerline sine wave. In each cycle, a binary '1' can be represented by a burst in the first zero crossing and an absence of burst in the second zero crossing. In the other hand, a '0' can be represented by the absence of a burst in the first zero crossing, followed by a burst in the next zero crossing.

The Start Code can start both on the sine wave transition of the zero crossing to the maximum (as represented in the following figure), or the zero crossing to the minimum.

The process starts with the Start Code, it comprehends 2 cycles and is characterized by the use of 3 bursts in the first 3 zero crossings and the absence of a burst in the last zero crossing, as shown in the following figure.

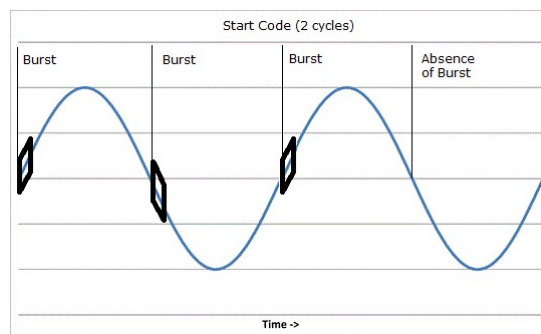


Figure 2.2: X10 based home automation units.

Ensuing is the House Code (A-P), with 4 cycles, and the Number Code (1-16), with 5 cycles. 4 bits allow a capacity of 256 different devices. This are the codes which identify a certain device and they make the condition for a certain device being activated.

In the following pictures are examples of the House Code and the Number Code, respectively.

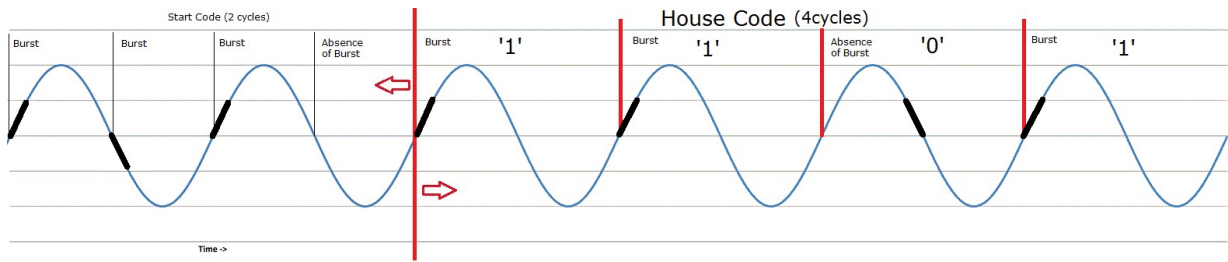


Figure 2.3: X10 House Code.

<b>A = 0110</b>	<b>E = 0001</b>	<b>I = 0111</b>	<b>M = 0000</b>
<b>B = 1110</b>	<b>F = 1001</b>	<b>J = 1111</b>	<b>N = 1000</b>
<b>C = 0010</b>	<b>G = 0101</b>	<b>K = 0011</b>	<b>O = 0100</b>
<b>D = 1010</b>	<b>H = 1101</b>	<b>L = 1011</b>	<b>P = 1100</b>

Figure 2.4: X10 House Letter Attribution.

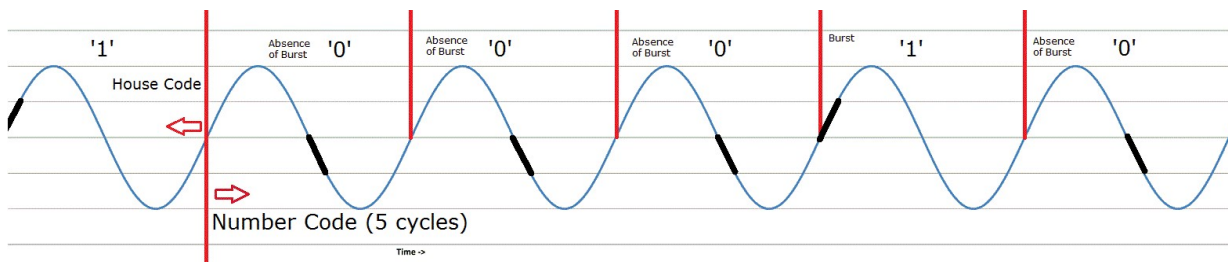


Figure 2.5: X10 Number Code.

<b>1 = 01100</b>	<b>5 = 00010</b>	<b>9 = 01110</b>	<b>13 = 00000</b>
<b>2 = 11100</b>	<b>6 = 10010</b>	<b>10 = 11110</b>	<b>14 = 10000</b>
<b>3 = 00100</b>	<b>7 = 01010</b>	<b>11 = 00110</b>	<b>15 = 01000</b>
<b>4 = 10100</b>	<b>8 = 11010</b>	<b>12 = 10110</b>	<b>16 = 11000</b>

Figure 2.6: X10 Number Attribution.

In the following figure is an example of how the user is able to change the code in this type of device.



Figure 2.7: X10 Number Attribution (extracted [12]).

One important thing to notice is that in the number code there are 5 bits, the last one of these 5 bits is called the function bit. If it is '0' it means the preceding data is the number code.

This 3 fields, Start Code, House Code and Number Code together made an Address Code. Next it will be explained the Command Code. Note that between changes from these codes (Address and Command), a series of six zero crossings must be completed in order to reset the shift registers.

Now regarding the Command Code, it starts with a Start Code as it was shown before. This is followed also by the House Code, a letter. Now, instead of the Number Code, a Command Code is transmitted (5 cycles). This is indicated by the change of value in the last cycle to 1. There are 4 bits left then. They have predefined functions as shown in table 2.1.

Both Address Codes and Command Codes must be transmitted twice in order to add redundancy and consequently more reliable transmissions [17].

#### 2.1.1.2 Advantages and Disadvantages

X10 is a technology that makes use of the electric grid present and this implies that it can be retrofitted in virtually every building. However the necessity of cables until every unit implies that if an area is not reached by cable trays is inaccessible for the system. X10 is also very prone to interference and has no error detection.

<b>Function</b>	<b>C3</b>	<b>C2</b>	<b>C1</b>	<b>C0</b>	<b>FB</b>
<b>All Units Off</b>	0	0	0	0	1
<b>All Units On</b>	0	0	0	1	1
<b>On</b>	0	0	1	0	1
<b>Off</b>	0	0	1	1	1
<b>Dim</b>	0	1	0	0	1
<b>Bright</b>	0	1	0	1	1
<b>All Lights Off</b>	0	1	1	0	1
<b>Extended Code</b>	0	1	1	1	1
<b>Hail Request</b>	1	0	0	0	1
<b>Hail Ack.</b>	1	0	0	1	1
<b>Pre-Set Dim</b>	1	0	1	0	1
<b>Pre-Set Dim</b>	1	0	1	1	1
<b>Ext. Data</b>	1	1	0	0	1
<b>Status=ON</b>	1	1	0	1	1
<b>Status=OFF</b>	1	1	1	0	1
<b>Status Req.</b>	1	1	1	1	1

Table 2.1: X10 function list.

## 2.1.2 HART

The HART (Highway Addressable Transducer) protocol is mostly used in the industry automation. The most important factor behind the technology adoption is the fact that it can run on the 4-20mA analog wiring systems, which are widely implemented. Being a smart slave protocol, HART communication is usually made between a smart device and a monitoring or control system [35]. HART superimposes digital communication (Bell 202 FSK) on top of the analogic 4 to 20 mA, which enables two way communication.

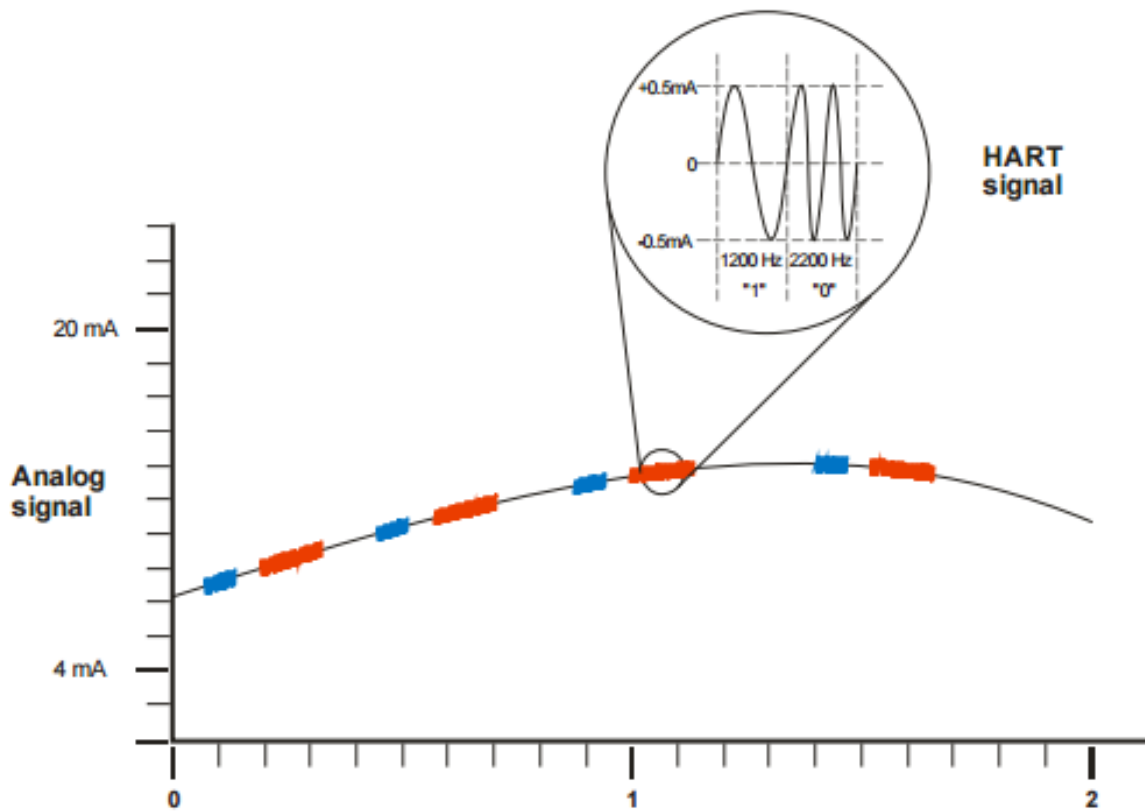


Figure 2.8: HART Frequency Shift Keying (adapted[35]).

There are two topologies used in HART communication Point-to-Point and Multidrop mode as represented in the next two figures.

The first, point-to-point, uses the 4-20mA analogic signal to transfer one process variable. Other process variables, parameters or data are sent digitally superimposing the 4-20mA signal without the original analogic signal being affected.



Figure 2.9: Two communication channels, Point-to-Point topology adapted[30].

The second topology, multidrop, allows for multiple smart devices to connect on the same pair of wires. This type of topology requires that every device has a specific address, whereas on point to point there is no such requirement. Multidrop mode is very unusual due mainly to the slow speeds [30] [31].

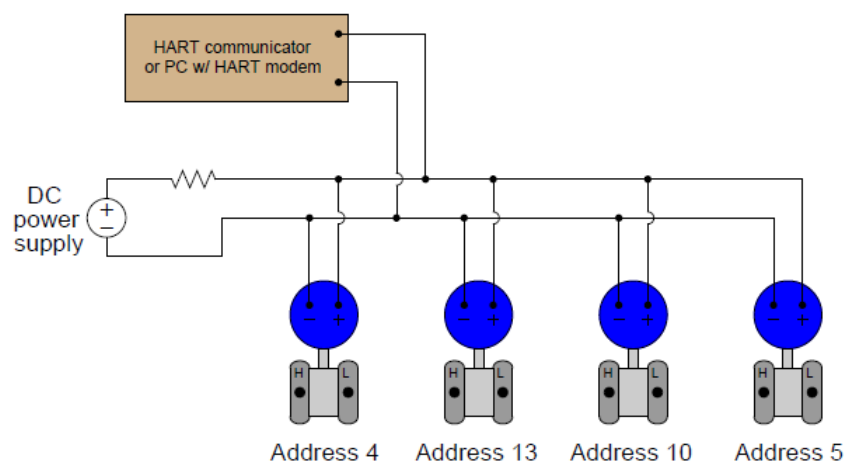


Figure 2.10: Multidrop communication(adapted[30]).

### 2.1.2.1 Advantages and Disadvantages

HART is heavily oriented to the industry, making use of technology that is not usually implemented in residential buildings. The technology is based on wired installations and this would make the residential integration difficult. The positive aspects of this technology are the ease on detection and troubleshooting of problems, fast device configuration and remote diagnostics without physical presence.

### 2.1.3 Z-Wave



Figure 2.11: Z-Wave units (extracted [13]).

The proprietary Z-Wave wireless protocol was one of the first projects of Zensys, a company founded in 1999. Z-Wave main objective is to produce wireless solutions for the thriving home automation market. In 2005, Zensys formed a global consortium which consists of industry leaders from all over the world. Their objective is to spread Z-Wave as the standard technology for every house automation device, regardless of the company that produces them.

One of the focus of this protocol is to keep the power requirements of the devices low. This allows devices to be powered by batteries which don't need replacement for years. The frequency of operation is ISM 915MHz (+/- 13MHz) in the USA (region 2) and ISM 868MHz in Europe (region 1), with GFSK modulation. This frequency avoids interference with other common wireless frequencies that are present in homes, such as Wi-Fi and Bluetooth. The throughput of the original technology was 9.6 Kbit/s to 40 Kbit/s, but recently devices managed to achieve a throughput of 100kbits/s.

Z-Wave uses a mesh network topology. Each network can have up to 232 nodes, which are divided in two categories: controllers and slaves. In this type of topology the information is passed from one node to another node (each one with a 30m covering indoors) and can

hop through a maximum of 4 nodes which is enough for the majority of buildings [13] [14].

The protocol stack of the Z-Wave communication system is shown in the next figure. The ITU-T recommendation G.9959 determine the physical layer and MAC (Medium Access Control) layer. It also defines some characteristics of the Transport Layer. The Network and Application Layer were developed by the Z-Wave Alliance and Sigma Designs.

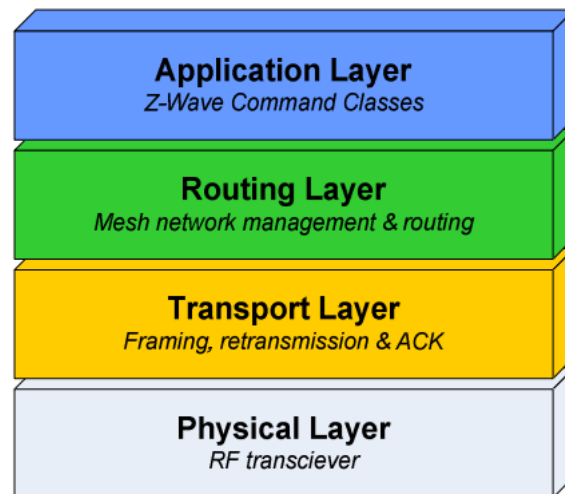


Figure 2.12: Z-Wave Protocol Structure (adapted [13]).

### 2.1.3.1 Network devices

Z-Wave uses source routing (SRA), which means that when the frame is created, the route that it will take is already defined and known by the elements. In this technology every device has knowledge of their own node neighbors and this makes simple the definition of the route for each frame. There are two main devices, controllers and slaves and two secondary devices, mobile controllers and routing slaves.

First we have controller devices, which are subdivided into primary and secondary controllers. Only one primary controller can exist in each network and it is:

- responsible for the communication of the Home ID. (unlike secondary controllers)
- responsible for the attribution of a distinct Node IDs for each device in the network.
- aware of the full network and therefore, can send messages for any terminal.
- responsible for the integration of new nodes into the network.



The slave devices are subdivided into slaves and routing slaves. The routing slaves have partial knowledge of the routing table. They can reply to a node that has sent a message and can start communication with pre-established nodes. On the other hand slaves can only reply to other nodes.

### **2.1.3.2 Routing principles**

The major benefit of the mesh network technology is that the controller doesn't need direct radio contact with the destination node. This improves range and reliability of the network. The primary controller has access to all the devices and their respective neighbors. This information, enables the creation of a table with every available route in the network. After this, the user, with help from various software solutions, can optimize the network.

- **Inclusion**

During this stage the Node IDs and primary controllers are assigned. First the primary controller is assigned. Next, the primary controller spreads the Home ID to all the other nodes. Finally, the controller assigns individual Node IDs to each node.

- **Exclusion**

During this stage the Node IDs and primary controllers are assigned. First the primary controller is assigned. Next, the primary controller spreads the Home ID to all the other nodes. Finally, the controller assigns individual Node IDs to each node.

### **2.1.3.3 Advantages and Disadvantages**

Z-Wave is a lot simpler to use than its rivals (*i.e.* ZigBee), yet it provides an array of basic functions that are adequate for most projects in home automation. The adoption of sub-GHZ frequencies decreases interference in communications, the main problem lays with the use of different frequencies for each region of the world, which translates in a necessity of different designs for each region [15] [16].

The use of Source Routing and the characteristic tree network topology of this technology makes the mobility a complex and power consuming procedure. The recourse to a proprietary radio protocol prevents progress at levels observed in competing technologies who use open radio protocols. The above aspects avert the technology from being a good perspective for the future of IoT.

### 2.1.4 ZigBee

The ZigBee Technology was developed by the ZigBee Alliance in the late 90's in order to improve what was already brought by other technologies such as Bluetooth, HBA and Wi-Fi.

This technology has a technical foundation on the low data rate IEEE 802.15.4 (IEEE 802.15.4 LR-WPAN) standard and the objective is to openly sustain and manage the emerging ultra-low cost and low power devices.

The protocol stack of the ZigBee communication system is shown in the next figure. The IEEE 802.15.4 determine the physical layer and MAC (Medium Access Control) layers and the ZigBee Alliance determine the Network and Application Layer (alongside the user), according to the OSI model.

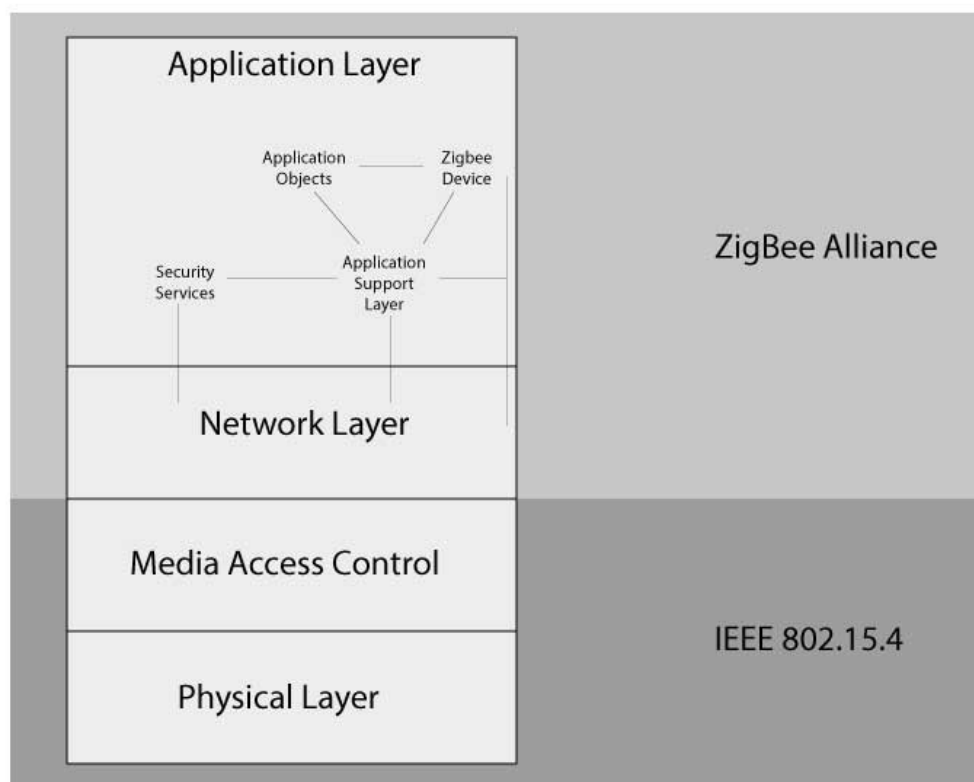


Figure 2.13: ZigBee Protocol Structure (adapted [18]).

With concern to overall functionality, the Physical Layer provides the general radio capabilities, the MAC Layer provides reliable single-hop communication, the Network Layer provides multi-hop and routing for networks of superior complexity, the Application Layer provides the management functions for network and devices and message formats, and finally, the Security Services Provider settle essential security services, such as node admission management and cryptographic key control, and the infrastructure trust of the network [18].

The frequencies of operation are the unlicensed bands of ISM 915MHz (+/- 13MHz) in the USA (region 2), ISM 868MHz in Europe (region 1) and finally and mostly used the ISM 2.4GHz (Region 1, 2, 3). It uses BPSK (binary phase shift keying) and OQPSK (offset quaternary phase shift keying) modulation. A maximum data rate of 250 Kbit/s can be achieved. Zigbee also uses mesh networking which as seen before improves reliability, flexibility and security. The main advantage of ZigBee relies on the extended period of time (years) that devices operating under this technology can function without the need for battery replacement.

#### **2.1.4.1 Advantages and Disadvantages**

The ZigBee mesh topology provides a self-healing, self-configuration and easy to install network. The specifications of the technology are readily available which boosts the technology coverage and the development of products.

ZigBee is not supported by iOS, Android, Windows so it cannot directly share information with smartphones, tablets or laptops. The low data speed, short range and costs of the modules are disadvantageous for the technology evolution. The discussed aspects cripple this technology probability to be the future in home automation.

### **2.1.5 Bluetooth and Bluetooth Low Energy**

The well known technology Bluetooth was first invented in 1994. It uses the ISM 2.4 GHz band and GFSK (Gaussian Frequency-shift Keying) modulation. Bluetooth uses master-slave communication, each master being able to communicate with up to 7 slave devices. The communication makes use of data packets. BLE (Bluetooth Low Energy) is today a preponderant wireless technology and is seen in action on:

- Smartwatches.

- Heart rate monitors.
- Location tags.
- Automotive sensors and ECU's (Engine Control Unit).
- Access and security in restricted areas.

This technology has a great advantage, it is present in virtually every user device. Specifically, the appearance of the technology in the laptop, tablet and smartphone makes the user interaction with the home automation system much more intuitive and readily available. The first versions of Bluetooth had quite limited range and data rate. This characteristics have been improving over the years, with the launching of new Specification Core's every couple of years.

Bluetooth Low Energy (BLE), was born from the joining forces of Bluetooth Smart and the Core Specification 4.0, during 2010. Since then, Core Specification evolved and is now at version 4.2. The main targets are the home automation, health and sports tracking industry [26]. This technology advancement has corrected some of the downsides that initial versions had such as:

- Number of active slaves is dependent on the implementation.
- Interference avoidance is made by frequency hopping.
- Necessary time to send a packet was decreased significantly, from 100ms to only 3ms, and was crucial in lowering the power requirements.
- Compatibility with Apple products.

The technology is designed from scratch to achieve reliable communications in the crowded ISM 2.4GHz band. The techniques used for interference avoidance are:

- Frequency Hopping: 40, 2 MHz channels to be chosen from.
- 3 channel for Advertisement: 2402, 2426 and 2480 MHz which are locate on IEEE 802.11 (WiFi) gaps.
- Busy Channel High Level Avoidance

#### **2.1.5.1 Technology Protocols and Characteristics**

The management of both connections and advertising in BLE is made by Generic Access Profile (GAP). First it must be defined the two types of devices that can coexist in a BLE

network.

- Central Devices (master) - the laptop, smartphone, tablet or building central processing unit (among others).
- Peripheral Devices (slave) - low power devices with very low processing power (some examples are: heart rate monitor, movement sensor, light switch).

The advertising is the process in which a device makes itself visible for central devices. This is achieved by sending out an Advertising Data payload. The frequency of advertising will vary with each specific device, a less frequent advertising will improve battery efficiency.

Additionally, if a central device needs more information about the peripheral device it will send a Scan Response Request and the peripheral will answer with the data (if available) using a Scan Response Data.

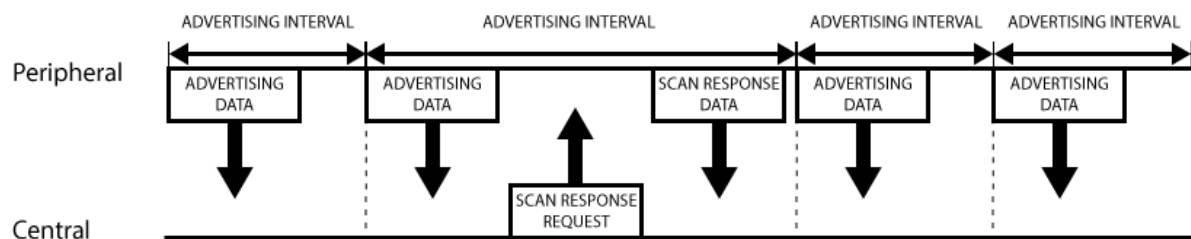


Figure 2.14: Advertising and Scan Response Example.(adapted[24]).

The other option is if a device needs to send data to multiple devices at the same time. The only way to do this is to make use of the broadcast properties of the Advertising Packet. The Advertising Packet has a 31 bytes payload that contains the description of the device, but it can be fulfilled with generic data. A second payload can be requested with a Scan Response. The downside is that being a broadcasted packet doesn't completely assure the communication safety.

Therefore, if one needs to send more than 2 payloads of data it or if data contents are private and need to be secured, a connection must be made.

When a connection is made between two BLE devices, Generic Attribute Profile (GATT) is made responsible for the communication. Once in a connection, a peripheral device can only be connected to one central device. A connection interval is proposed by the peripheral and the central will make a connection in each interval if new information is

available from the peripheral. The advantage of a connection is, along with security, higher data throughput and data organization.

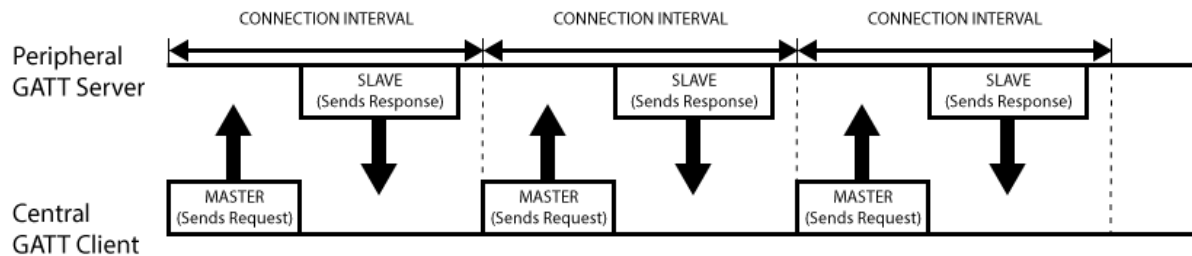


Figure 2.15: Connection interval Example.(adapted [24]).

With Specification Core 4.1 however, any device can act either as peripheral or central. Also, a peripheral can be connected to multiple central devices and central devices can be connected to multiple peripheral devices.

### 2.1.5.2 Advantages and Disadvantages

The main advantages are:

- **Low Power**  
Bluetooth Low Power devices can last for years on coin batteries.
- **Ubiquity**  
The compatibility of older and newer Bluetooth Specifications together with the global application of bluetooth in every electronic device resulted in an unparalleled ubiquitousness.

The disadvantages are:

- **Range**  
The communication range of Bluetooth Low Energy is proportional to the transmission power of the antenna which in turn is proportional to battery usage. Other factors such as the transmitting medium, the antenna topology can influence range but in a clear line of sight transmission ranges of 30 meters were already achieved.
- **Data Rate**  
The theoretical limit for data rate is 1Mbps yet this value suffers with a variety of

factors such as radio transmission limitations, CPU availability and software constraints. This implies that a practical upper limit must be set and, with a general set of peers, this value is generally 10Kbps. This may seem like an extremely low value when compared with other technologies but Bluetooth Low Energy focus is not high throughput but instead increasing life expectancy of the batteries in BLE devices.

### 2.1.6 EnOcean



Figure 2.16: EnOcean based Neptronic products. (extracted [33]).

The EnOcean technology is an energy harvesting wireless technology that has focus on building automation, transportation and domotics. The purpose of this technology is to produce systems that don't require battery replacement. EnOcean makes use of renewable and sustainable energies present in the environment in order to make all the devices function. With conscience about the rise in the costs of energy, economically and environmentally, this technology seeks a minimal footprint with state of the art energy harvesting techniques.

Common sources of energy for devices based on this technology are temperature variations, ambient light and the mechanical movement of turning on or off a switch.

In the same path as some technologies analyzed before, the EnOcean created a non-profit Alliance with the objectives of promoting the technology, standardizing it and create interoperability between industrial, commercial and residential buildings.

The technology runs, in Europe, on the ISM 868MHz frequency band, with a ASK (Amplitude Shift Keying) modulation format, and in, USA and Canada, it uses the 315 MHz frequency band. The data rate is of 125kbps and the protocol stack (OSI model) is built with 3 layers: network, data link and physical. The range is of 30 meters indoors but can be expanded by using signal repeaters [32] [34].

#### **2.1.6.1 Advantages and Disadvantages**

A technology that can harvest the necessary energy for devices to transmit and receive data decreases its costs of device maintenance (no need for battery replacement) and also the costs of energy. This is the main contributing factor for the “exponential growth on demand” that EnOcean experiences in their products.

The wireless characteristic of the technology removes a lot of the retrofitting issues, which decreases costs of installation and maintenance and increases the overall market for the products.

On the other hand, this kind of technology can only be used for sensing. Currently, only a relatively small amount of energy can be harvested with this technology and it is not enough to use on actuators.

#### **2.1.7 WirelessHART**

WirelessHART technology is an addition to the legacy of HART (Highway Addressable Transducer) protocol. This technology features:

- Wireless capabilities.
- IEEE 802.15.4-2006 Physical Layer
- Self-healing: alternative paths adopted if obstructions and signal degradation are present.
- Security:
  - Network Protection: frequency hopping, message integrity check.



- Information Protection: 128 bit AES, device authentication.

The protocol uses 2.4GHZ ISM frequency band and complies with radio IEEE 802.15.4 standards. The main idea of this technology is to simplify the addition of new units of measure by decreasing the time of implementation and costs of installation and at the same time maintain the security of the network WirelessHART presents the following types of devices [22]:

- Security Manager: manages security issues.
- Network Manager: configures the network and schedules the communications.
- Gateway: connects multiple field devices with the central automation system, through access points.
- Access Points: attached to the gateway, they provide redundant paths between the gateway and the network.
- Routers: boost network connectivity and coverage.
- Field devices: sensors and actuators.

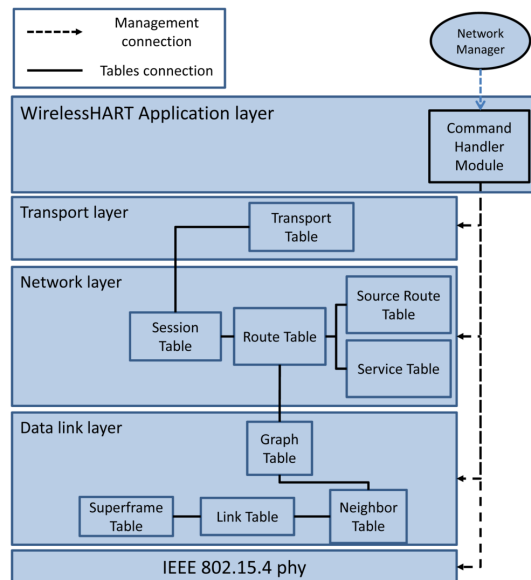


Figure 2.17: WirelessHART protocol stack.(adapted [22]).

### **2.1.7.1 Advantages and Disadvantages**

As seen on other technologies, security on WirelessHART is solid [21] due mainly to the use of the advanced encryption standard (AES). This standard has, however, some risk associated with it because it requires that a private key is shared prior to the communication.

The WirelessHART brings up front cost reductions associated with the virtually nonexistent requirements of infrastructure and cabling. Savings are also prevalent in terms of labour and permits when compared with wired implementations.

Another advantage of this technology is the very high reliability provided by the Time Synchronized Mesh Protocol and the self-healing, self-organizing mesh network [20].

## 2.2 Technology Overview

The traditional wired networks, such as the studied X10 and HART, require very intensive planning to accommodate all the wiring, cable routing, connectors and sensors. Simultaneously, the necessity of cabling until a sensor, implies that if it is unreachable to cable trays, then it could not be part of the system. The flexibility on wired technologies is extremely low when compared with wireless, if new units need to be installed in addition to the network there is a necessity for work permits, isolation processes and the inevitable cabling. A routine verification on the installation is also necessary which greatly increases the economic factor.

Characteristics	Wireless	Wired
Installation	SIMPLE	COMPLEX
Throughput	LOW to MED	HIGH
Reliability	HIGH	HIGH
Range	HIGH	LOW
Overall Cost	MED	HIGH

Table 2.2: The Confrontation between Wired vs Wireless

On the other side, wireless technologies, such as Bluetooth and WirelessHART provide minimum engineering effort and significant economic saves during the implementation and maintenance phase.

	X10	HART	Z-Wave	ZigBee	BLE	EnOcean	WirelessHART
Freq. Bands	-	-	915MHz,(USA), 868MHz,(EU), 2.4GHz	915MHz,(USA), 868MHz,(EU), 2.4GHz	2.4GHz	915MHz (USA), 868MHz (EU)	2.4 GHz
Modulation	OOK	FSK	GFSK	BPSK, QPSK	GFSK	ASK	O-QPSK
Spread Spect.	-	-	-	DSSS	FHSS	-	DSSS
Indoor Range	-	-	30m	10m	10m	30m	50m
Security	NO		YES	YES	YES	NO	YES
Energy Req.	HIGH	MED	MED	MED	VERY LOW	VERY LOW	MED
Cost	MED	MED	MED	VERY LOW	MED	LOW	HIGH
Public Specs	YES	NO	NO	YES	YES	YES	NO
Data Throug.	20b/s	1.2Kb/s	100kb/s	250Kb/s	10Kb/s	125Kb/s	250Kb/s

Table 2.3: Confrontation between the different researched technologies

X10 was a good starting point to obtain a better overall understanding of the domotics technology. The extremely low data rate limits severely what can be done with this technology. Also, but not less important, is the bulky structure of the products that are based on this technology. ZigBee and Z-Wave are very used in the development of home automation projects which means there is a lot of experimentation and information available and many projects done with these technologies. The energy requirements, however, are not following the mainstream which leads to very low energy requirements. BLE based and EnOcean devices have quite interesting features, very low energy requirements and environment energy harvesting, which makes them very good prospects to the future of home automation.

### **2.2.1 Implementation Size and Market Adoption and Standardization**

Regarding this aspect the powerline approaches are the most problematic. Most of this technologies (X10, KNX) must have quite bulky structures. This is partially because of the obligation for voltage converters and heat sinks, these are imperative when transforming powerline voltages into low electronics voltages. ZigBee and Z-Wave are quite smaller. Between this two, ZigBee has to support a wider range of applications, this results in a larger space requirement to accommodate structures that deal with all of them. BLE has shown modules that are incredible small, necessity brought by thinner and thinner devices, BLE is undoubtedly very interesting choice when regarding dimensions.

In terms of market adoption and standardization, both ZigBee, Z-Wave and BLE have a clear upper hand. Both these technologies have powerful consortia, many industry leaders, spreading products towards the whole world. ZigBee however has shown some lag in bringing products to the market, the first products were only available in mid-2009, contrasting Z-Wave that brought products in the last turn of the millennium. BLE has the already explained ubiquitousness that is incomparable with any other technology hereby studied.

### **2.2.2 Security Protocols**

Today, security is one of the top priorities in every technological enterprise. This is essential in a world where a residential building can be remotely controlled. For this reason, every domotics wireless technology must have one or more ways for securing the information that

is shared within a network, this is made by some (BLE, Z-Wave) by making use of Advanced Encryption Standard 128 (AES), and others (EnOcean) by using rolling-code.

In powerline technologies, this issue is not as relevant. The information runs inside the power lines, inside the building, which makes it moderately resistant to eavesdropping from someone outside the building.

# Chapter 3

## Acoustic Sensing Solution

### 3.1 A Wireless-based Sensing Network in Home Automation

This chapter presents a detailed description of a innovative house automation system. This new proposal is the fruit of thought and reflection about the functionality and the flaws in existent modules and technologies in home automation. From there, starts the development of a new solution that can change the interaction with the building. Unlike the existent user interactive screens or switches, what is proposed is to use the wall itself to make use of the smart home fixtures.

The implementation objective is to detect one or multiple knocks on a wall, with resource to environmental information gathering, and share the information with a central gateway, which can be a smartphone, a microprocessor or a laptop, as long as it has Bluetooth connectivity. Thus, the implementation will provide a viable and useful alternative to mechanical switches and touch screens. Such system will reduce costs when compared to touch screens and flexibility when compared to traditional mechanical wall switches. The networking of sensors and communications is also approached as an alternative to the well known PICONET and beaconing, the new approach is oriented to the proposed system.

At the same time the system, with very little alterations, can be implemented as a security breach detector, in which a touch on the wall is categorized as an intrusion and the breach is forwarded to the gateway.

Sharing the information with a gateway, for example, a smartphone or a laptop, opens the possibility for the information to be spread to any other user devices with internet access.

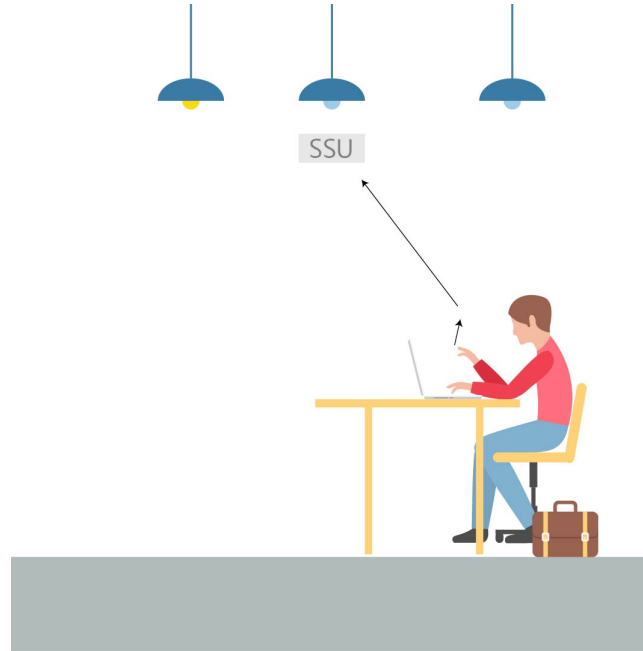


Figure 3.1: Application Example of the new proposal (SSU- Smart Sensor Unit).

In order to incorporate wireless into a building, the coexistence with wired fixtures must be ensured. The proposed solution will be an alternative to the traditional switches, notwithstanding the present switches can be either kept on functioning, ignored or preferably removed. The different function of the wall knocks can be programmed both during installation or later, at any chosen moment, due to the fact that they are changed in the central unit (gateway) of the building.

The fundamental solution requirements are:

- Wireless Communication.
- Low Energy Consumption.
- Detection of environment changes.
- Intercommunication with the central unit.

The system has the ability to control any integrated part of an automated home. The information received from the wall can be interpreted in different forms and this can be



changed in the central unit, via software or hardware.

There can be several units gathering information around the house, each unit will receive data from the wall where it is present on. If the wall however is of large dimensions, the installation of several units might be necessary.

The relative position of the unit on the wall is of relevance and the closer it is to the usual knocking position the better results are expected.

## 3.2 Scenario

In Europe, the brick construction with concrete floors is the most used construction technique. This is essentially because of the structure strength, the good isolation and the very low costs of materials. The electric installation of a brick house is considered very inflexible, unchangeable, and this goes in the opposite direction of what people need [40].

The building wiring classic installation uses cabling and cabling trays that go through walls until a power socket or light control switch. In the last decade, the introduction of *pladur* walls and ceilings provided a certain degree of flexibility in cabling and access to new home functions, but rearrangement is still very labor intensive.

Some recent constructed and renovated buildings are being already implemented with central processing units (gateway) and this units, similarly to any other processing unit, can be programmed via software or rewired via hardware, in this last case for the addition of new house automation devices, functions and user interfaces.

Three of the most common additions to the traditional installation (basic light switch and power sockets) are motorized blind covers, motorized doors and electromagnetic locks.

In light control switching, the most commonly used are the mechanical ones, which change from zero resistance (ON) to infinite resistance (OFF). In recent buildings and in renovations however, lighting with intensity regulation, with the use of a potentiometer, is commonly adopted.

In electromagnetic locks, the door frame contains a magnet and the door a metal plate. When the door needs to be locked, the magnetic material is connected to a current source, which can be powered by both the build electrical system or batteries. When the door needs to be opened, a simple break from the current source will stop the magnetic field from pulling towards the metal plate [40].

Electric window blinds are the modern curtains, they incorporate a motor that physically closes or opens the blind. This system is usually actuated with two switches, one for pulling up and another for pulling down [29].

Motorized doors are quite common due to practicality. Ordinary systems use wireless communication between a remote control and a receiver in the system enclosure.

From the previous analysis of the construction, the study of both existent and unfinished domotic fixtures, follows the proposition of a new system, a solution that consists in the development of a sensing module that retrieves information, specifically a knock (or more) on the wall and transmits this information to a central gateway which, in its turn, has the responsibility to activate or deactivate the respective actuators.

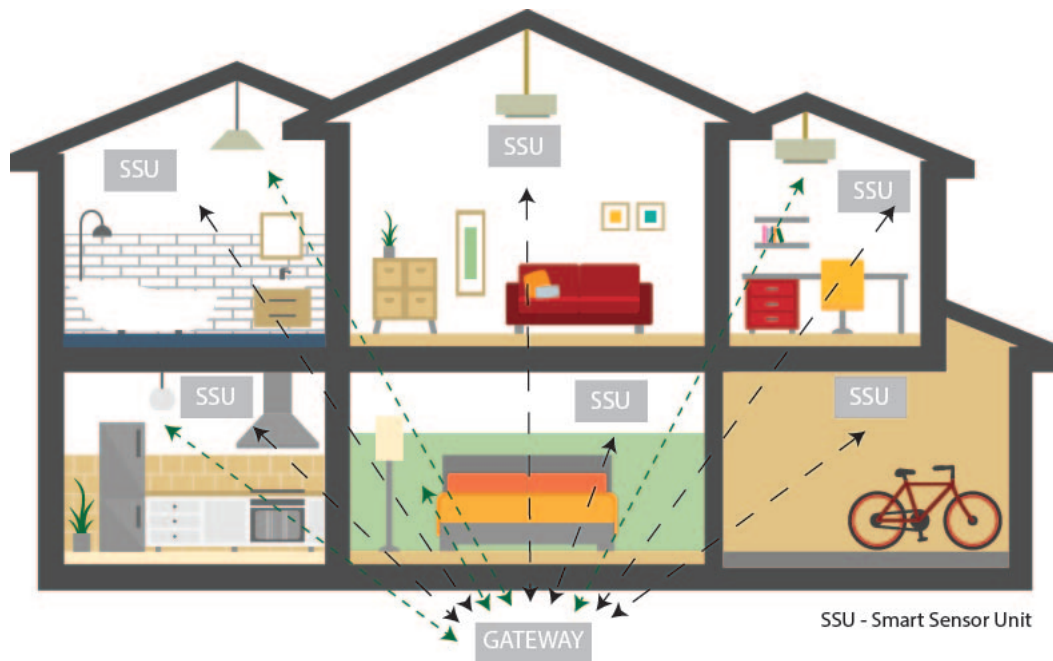


Figure 3.2: House Network with multiple Smart Sensor Units.

The solution fundamental objectives are to eradicate the need for the classic wall power switching, which by itself can be a big step in the process of changing from wired to wireless, and to make the information obtained on a wall accessible, by using a secure, reliable and widely present wireless technology. It is a strong conviction that this system will bring advantages in terms of:

- Comfort, minimal physical effort to perform the same functions.

- Cosmetic appearance, the absence of light switches can be appealing to modern architecture projects.
- Security, a unexpected touch on a wall can be the sign of home intrusion.
- Safety, due to the absence of electric wires.

### 3.3 Architecture Block Diagram

The three major parts of the smart sensor unit are the communication part, the data processing part and the environment detection part. The Communication Interface is a transceiver and has to establish two kinds of connections, one with the Home Automation processing unit (or gateway) via radiofrequency and other with the microprocessor. The gateway shown on the following diagram is only for demonstration purposes, in a real building implementation it has to be integrated in the building. This system require testing the success of communication with a gateway so it was simulated with another communication transceiver, a microprocessor and an actuator (relay with multiple channels).

The basic block diagram for a unit is shown in the following figure.

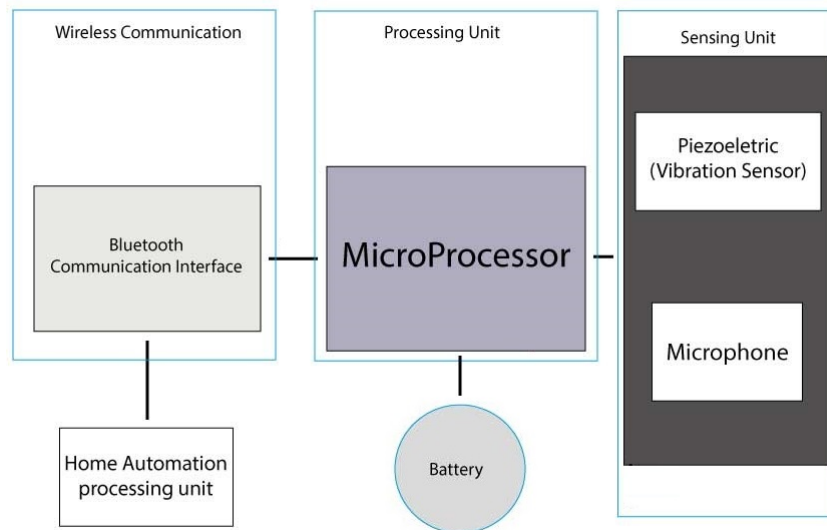


Figure 3.3: Block Diagram of the Proposed Architecture.

In the end, the module is stimulated by an external disturbance, noise and vibration (from

the knock) which is detected by two types of sensors, each oriented to the respective disturbance.

Next, the sensors send this information to an interrupt port on the microcontroller. The central processor process the information read from the sensors, by making a decision based on intensity and reception time. If the external disturbance is positively detected as a knock, then the microprocessor wakes the communication interface, which starts the advertising process.

A central gateway is constantly in search for the SSUs and when one of the SSUs starts advertising, decides if the connection is or not to be made. This decision is made by reading and analyzing the flag value, which is associated with the intensity of the disturbance. The two devices stay connected during a window time in order to transmit more knocks, until a maximum of 3. The matching function is activated.

The transceiver has to trigger a connection, the decision was to use a changeable field in the advertising packet to transmit the information of the disturbance. Using this field allows the system to discard unwanted knocks detected by other modules and also transmit the intensity of the detected disturbance which can be correlated with the distance of the knock.

The microprocessor is required to have low energy consumption, serial communication for the connection with the transceiver, Analogic to Digital Converter(ADC) ports with interrupts to establish connection with the sensing unit, and a low energy mode for long periods without use.

The sensing unit is composed by a piezoelectric sensor which detects deformations in the medium and a microphone which detects sound from the medium. The confrontation of the information will allow for a knock detection.

For an effective implementation the required items for a smart sensing unit are:

- Microcontroller.
- Communication Module.
- Piezoelectric Sensor.
- Sound Detection Module.
- Microphone.
- LED light fixture.

- Passive electric components.

For the simulation of the central home processing unit it is used:

- Microcontroller.
- Communication Module.
- Relays.
- LED light fixture.

## 3.4 Implementation

The implementation of this system is based on 3 peripheral units and a central unit. These units can send and receive information to others and to the central unit, however the crucial communication transmission is between the sensor unit and the home central unit and vice versa.

Through the peripheral units the wall interaction is detected and this information is forwarded to the central unit wirelessly. The central unit represents the gateway of a house, and processes the information sent by the peripheral units. The central unit also decides what are the peripheral units to prioritize.

This section presents the development of a system and the respective software and hardware.

### 3.4.1 Microcontroller

ATMEL ATmega328P is a widely used microcontroller. This device is selected mainly because of the very low cost and low power consumption and availability.

#### 3.4.1.1 Arduino and ATmega328P

Arduino Uno is a microcontroller board based on the high performance 8 bit microcontroller ATmega328P-PU. This means the two share a lot of the features.

The ATmega328P-PU when used with the Arduino Uno board has the main features needed to have communication with another Microcontrollers and features needed to receive and

process information from a variety of sensors. The communication between two microcontrollers is obtained by a SPI port (or UART port) and the respective library that allows fast communications between microcontrollers, in this specific case with the intervention of a radiofrequency module. With the goal of receiving in a correct manner the information gathered by sensing units, composed usually by analog and/or digital sensors, this kind of microcontroller possess 6 analog inputs/outputs and 14 digital inputs/outputs.

It is recommended to power the board within the range of 7 to 12V. This can be from a USB source, a power supply or a battery. The programming of the UNO isn't dependent on any external hardware because of the bootloader pre-installed on the microcontroller.

Even though, the Arduino runs on 5V, it incorporates a regulator circuit that gives the user access to a safe 3.3V port. This is quite important, since today, there are a lot of sensors and communication interfaces that run on the 2.7V to 3.6V range.

#### **3.4.1.2 Integrate Development Environment (IDE)**

Arduino produces today a large variety of boards. These boards consist in one microprocessor and external components which help on the software development. Also available online and freely is the IDE (Integrated Development Environment) which makes it easier to program and debug different programs in different boards. This easy to use software may show some limits when developing advanced applications.

#### **3.4.1.3 Energy Consumption**

Atmel AVR microprocessors also have six power saving modes which give a lot of flexibility for low power applications.

In Power-Down Mode PIC32 consumes 0.41uA and ATmega328p consumes 0.1uA.

When active, ATmega uses 0.2mA and PIC32 uses 0.5mA (both at 5V). With a battery of 3500mAh, PIC would theoretically last for approximately 9 months on active mode and ATmega328p would last for almost 24 months [23].

#### **3.4.1.4 Interfaces with external devices**

ATmega328p has one USART (Universal Synchronous/Asynchronous Receiver/Transmitter), this type of port allows for UART communication and synchronization. A SPI master/slave

is also available.

The microprocessor is embedded within the Arduino Uno board which facilitates connections, provides over powering protection and has led's that give the developer useful information on the processing situation..

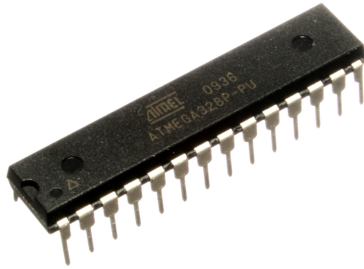


Figure 3.4: ATMega328P microprocessor (extracted[23]).

The Arduino Uno states is shown in the next figure, there are 2 main functions, the `setup()` and `loop()`. The `setup()` function is to be run once every time the reset button is clicked or the reset pin is set to 0V. The `loop()` function runs over and over after the `setup()` function is finished, until the reset is made.

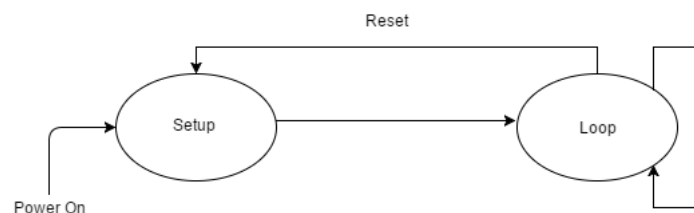


Figure 3.5: Arduino state diagram.

On the peripheral unit, the `setup()` function is responsible for:

- Start the serial ports,
- Set the initial role as a slave
- Define the advertising interval
- Reset the communication module (necessary for changes to take place).

- Define the output and input ports.
- Put the device under `POWER_MODE_IDLE`.
- Deactivate the unnecessary hardware.

The `loop()` function that starts running afterwards, is composed by a routine that keeps reading values from the USART/ADC ports. Once, a valid value is detected it stores it and moves into a loop function that makes a pre-determined number of ADC readings, and averages them, to improve the accuracy. The function analyzes this values by: comparing them with the standards and assuring they were synchronized.

If the microprocessor of the peripheral unit receives invalid information of the sensors or a connection is not established during a certain time window it will return to the `POWER_MODE_IDLE`.

If the knock is considered valid and passes the tests the program enters in the communication section.

## **3.4.2 Communication**

### **3.4.2.1 Approach to BLE 4.0 communication**

The HM-10 module was the selection for the development of this solution. Bluetooth Low Energy not only respects the necessary requirements, but it is irrevocable that the presence in more than 2 billion devices (Bluetooth enabled devices) increases the chance of the data collected by this sensors to be integrated and shared with the user personal devices. The wireless communication device has the option for the different system units to communicate between themselves and with the home central processing unit. A circuit breakout board to facilitate the integration within this project.



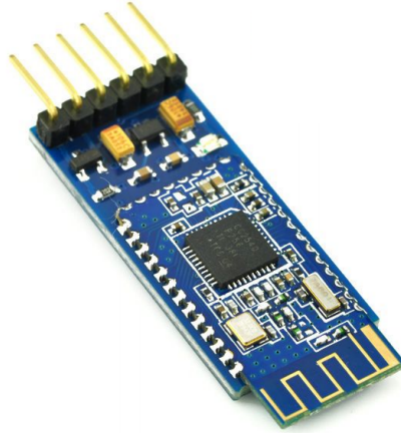


Figure 3.6: The HM-10 breakout board (extracted [43]).

HM-10 is a Bluetooth Specification V4.0 solution that enables robust and low cost units. It features the option to choose either the role of master or slave. This is achieved by the incorporation of the system-on-chip (SOC) CC2540/1, from Texas Instruments. The transmitting power can be programmed to be between 0.01mW and 5mW.

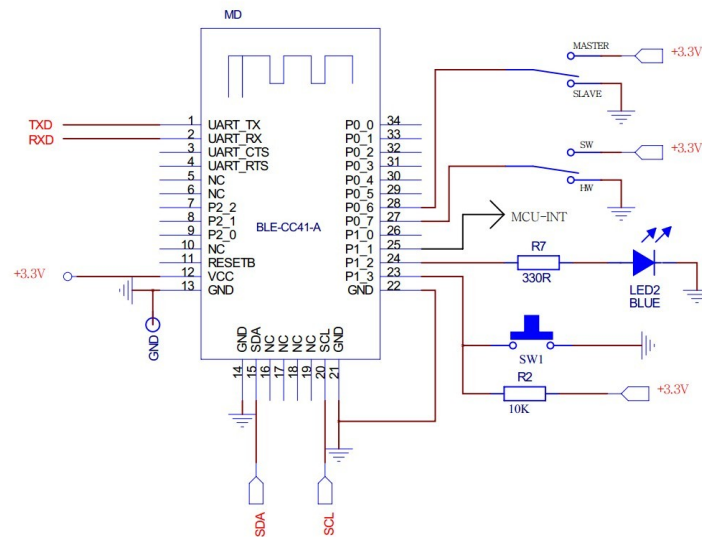


Figure 3.7: CC41A Breakout Board Schematic (extracted [43]).

It incorporates a sleep mode that consumes only 400uA-1.5mA and an active mode with a current consumption of 8.5mA, this allows for years of battery life on regular batteries.

It makes use of the UART interface and the communications is made via AT commands (derived from Hayes Command Set) which consists in a set of small strings that can be combined. First, it is required to set some parameters in the device, the baud rate, Parity, and Data Bits and Stop Bits for example. After this, an AT command to set the module as a master or a slave is required.

Some other important specifications for this module are:

- Security assured with Authentication and Encryption.
- Working Temperature from -5C to +65C.
- Dimensions of 26.9x13x2.2mm (Height x Width x Thickness)

An overview on the structure of the peripheral units is shown in the next figure. The message is sent by the microcontroller to the module via the UART pin and is received by the receiving module which transmits it, via UART, to the respective RX pin, in the microcontroller.

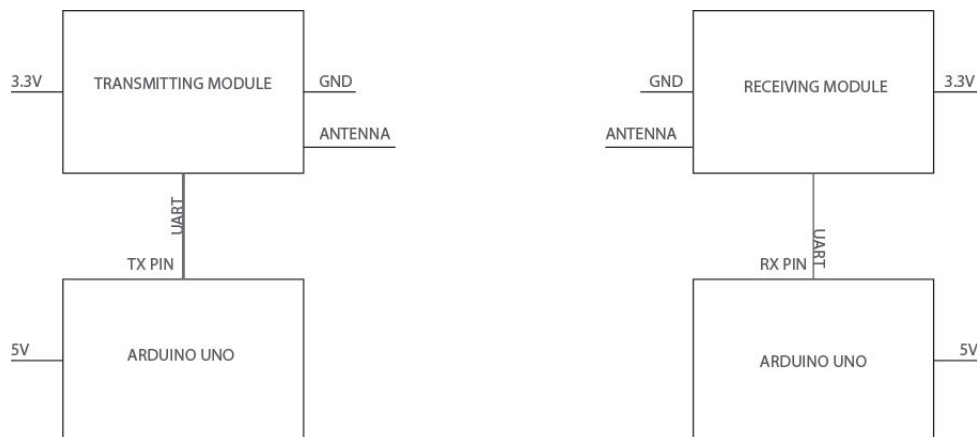


Figure 3.8: HM-10 modules function.

In the first phase of the implementation it is necessary to organize all the 3 Bluetooth modules in a master (central) or slave (peripheral) role and change the factory names.

In order to use the Arduino Uno as a USB-UART converter, the microcontroller needs to be uploaded with an empty sketch, which bypasses the existent bootloader

The Arduino is uploaded with an empty sketch and the HM-10 modules connected to the RX and TX ports of the Arduino.

The HM-10 module functions at 3.3V and the Arduino at 5V, a voltage divider needs to be used in order to convert the voltages between these two circuits.

All Smart Sensor Units are at this point defined as peripherals and their name is configured to HM1, HM2 and the central unit as HMC and given the role of central.

The Arduino IDE has an integrated Serial Monitor. Using this monitor, the AT commands AT+NAME and AT+ROLE are sent. The MAC address of each peripheral module is also retrieved with AT+ADDR comand in order to identify each member of the network, further in the project.



Figure 3.9: Role and name configuration on the HM-10 modules.

Send	Receive	Par	Description
AT	OK OK+LOST	NONE	Test Command
AT+ADDR?	OK+ADDR:MAC Address	NONE	Query module MAC address
AT+ADTY?	OK+Get:[para]	NONE	Query Advertising type
AT+ADTY[para]	AT+ADTY[para] OK+Set:[para] para:0~3	0:Connect by any device 1:Allow to connect with last succeeded device (within 1.28s after power on) 2:Allow to broadcast and scanning 3:Only advertising Default:0	Set Advertising type
AT+CONN[para1]	OK+CONN[para2]	para1: 0~5 para2: A , E, F A: Connecting E: Connect error F: Connect Fail	Try to Connect to device with given address
AT+ADVI?	OK+Get:[para]	None	Query Advertising Interval
AT+ADVI[para]	OK+Set:[para]	para: 0~F 0:100ms 1:152ms ...	Set Advertising Interval
AT+CLEAR	OK+CLEAR	None	Clear last connected address

Table 3.1: List of AT Commands used with the HM-10 BLE modules (adapted: [43]).

The next figure continues to describe the peripheral unit working method. As discussed before the peripheral unit will initially be put under a low power mode (`power_mode_idle`) which allows for individual hardware parts to be disabled (`adc`, `timers`, `spi`, `twi`). In this mode the USART /ADC ports will be active and waiting for a signal to be transmitted. This mode also assures no serial data is lost.

A medium disturbance will set one or the two sensors active. The microcontroller receives the information via USART/ADC from this sensors, and by testing the values against reference values and by checking if they were made simultaneously make the decision if the sensed disturbance was a real knock or not.

If the peripheral microprocessor assumes a knock was made, sets the advertising flag with a value proportional to the knock intensity by using the AT command `AT+FLAGvalue`. The value is calculated by transforming the value from a range of 0 to 1023 to a range of 0x00 to 0x10 (ex: values from 200 to 300, attributed 2, 301 to 400, attributed 3; least significant bits discarded). It then activates the Advertising process. The central unit decides (by analyzing the flag from the Advertising modules) which peripheral is to establish a connection. The central unit does constant readings from the advertising units.

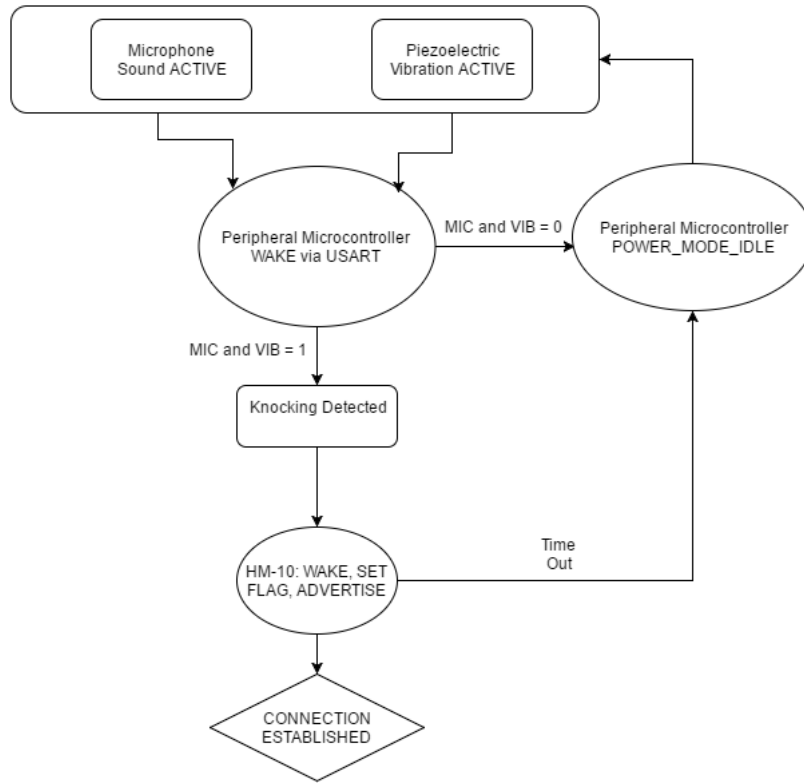


Figure 3.10: Working diagram of the peripheral unit.

The central unit Arduino is uploaded with a program that contains the algorithm with a conditional expression. If this condition is satisfied it then activates one of the pins 3, 4 or 5, that are connected to IN1, IN2 and IN3 in an external 3-channel relay. The relay can be connected to any electrical ON-OFF device, for the purpose of this implementation it was connected to 3 led lights.

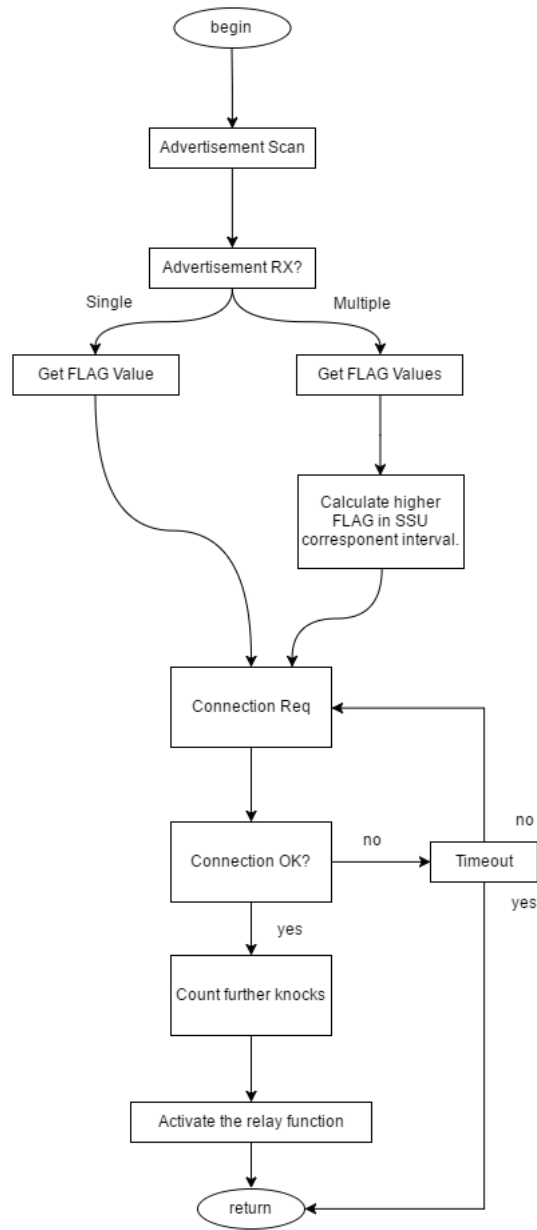


Figure 3.11: Master's flowchart.

Bluetooth 4.0 Specification allows for the Smart Sensor Unit (SSU) to Advertising Periodically via AT commands.

A sketch uploaded within the Smart Sensor Units has a conditional expression that if both sensors are activated it changes from sleep mode to active mode, with the transmission of a long string (80 characters) to the HM-10 module, and changes the FLAG value from an invalid value (defined in the algorithm) to a value that allows the central unit detect as

the wall was knocked on (this is made using the AT command AT+FLAGvalue, with value varying between 0 and FF, hexadecimal).

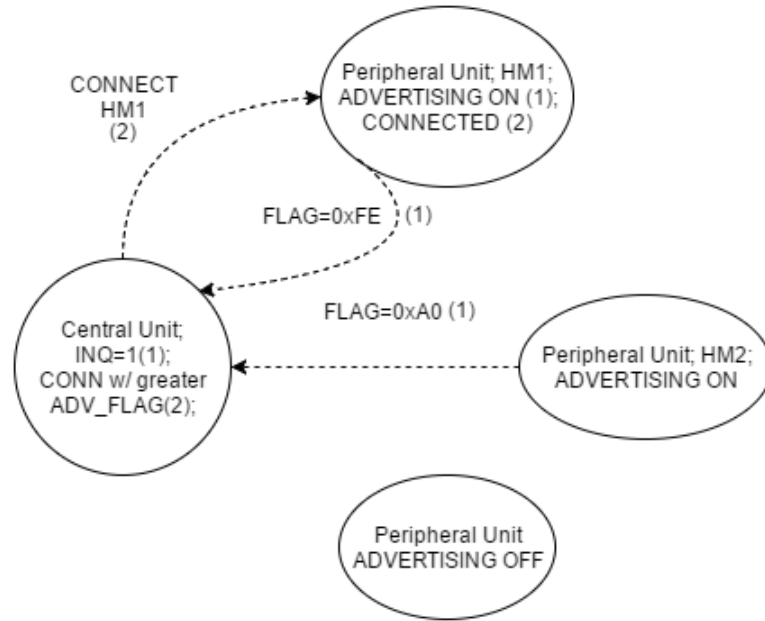


Figure 3.12: Structure of the advertising and connect process. Two phases, (1) and (2).

Both central unit and peripheral are put into a connected status for 1 second. This is achieved by using the `Millis()` function of Arduino. This function counts the time in milliseconds since the start of the program. Attributing a constant with the value of 1000 and comparing this value with two readings of the `Millis()` function allowed for a simple second counting. During this second if another knock is transmitted by the same SSU, besides the connection window being extended for another second, it is summed up in a variable.

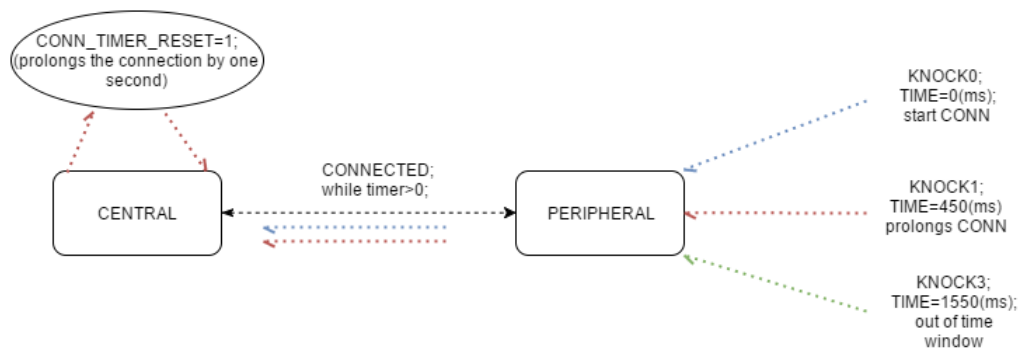


Figure 3.13: Diagram of the knocking and following events.



The number of knocks detected in combination with the FLAG received during the advertising period allows the central unit to assess what wall and what function of the wall is to be activated. After this period the central unit returns to an unconnected status.

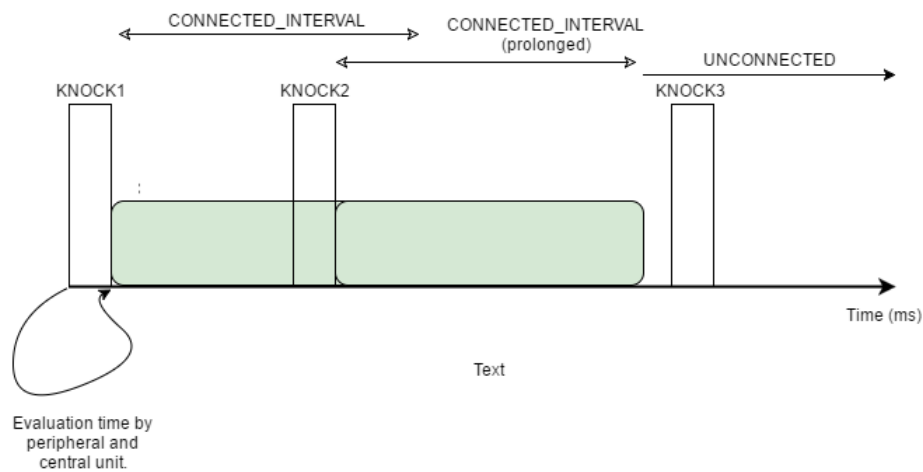


Figure 3.14: Time graphic of the knocking and following events.

If another unit transmits a knock during this time window, this advertising is not be attended by the central device while on connected status. This is not problematic in implementations where an intermediary gateway, for example, per room, is used. If too many peripheral units are attached to a single central unit, delays can be experienced. The timeout for a peripheral unit advertising must be set with regard to the number of peripheral units. The Smart Sensor Unit communication module, once disconnected, is put in sleep mode for power saving, via AT+SLEEP command.

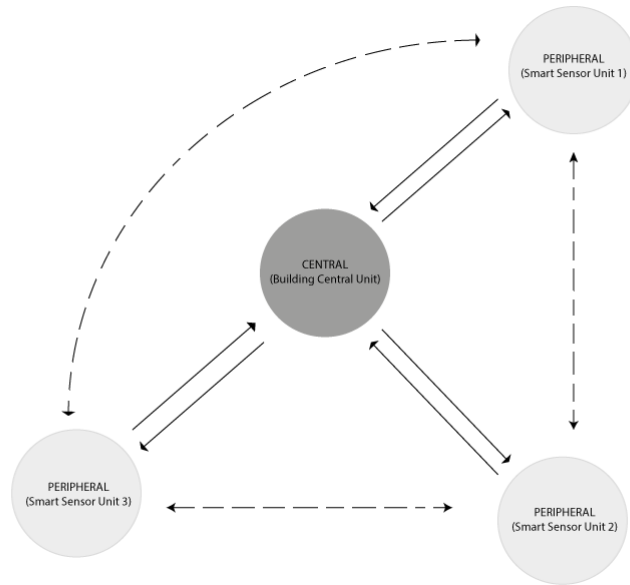


Figure 3.15: Network and Communication Links.

# Chapter 4

## Results

### 4.1 Sensing

The sensing capabilities of the Smart Sensor Unit are traduced into the microcontroller through the analog inputs, for the analog piezoelectric sensor, and through the digital inputs, for the digital microphone sensor. The use of only one of this two sensors is not viable because in a room loud noises or accidental touches on the wall could trigger the system. However the combination of this two sensors is very promising, with the main objective of the correct detection of knocking sounds.

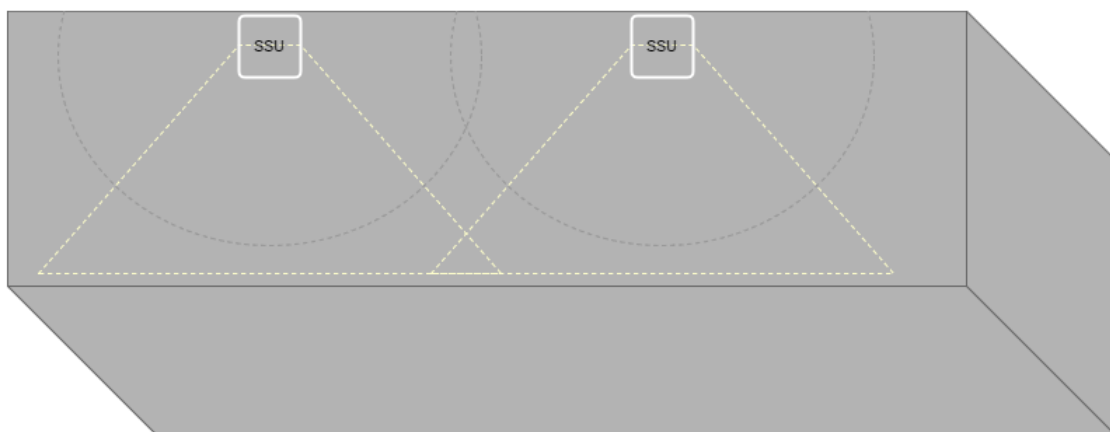


Figure 4.1: Areas of actuation of two sensor units on the same wall.

From here, the reference of “1 knock“ means a single knock during a time window, “2 knocks“ two consecutive knocks during a time window and further on. A user friendly manner to control a room is 1 knock for entering the light switching control, and then use, in a consecutive time window 1 or more knocks for different configurations in the lighting features, this can be both the intensity and individual lights. With “2 knocks“ the door lock is opened or closed with regard to the previous state. With “3 knocks“ the window cover (or covers in the case of multiple windows in a single wall) is opened or closed and the system keeps sensing in order to pause the window cover in other position that is not open or closed. It’s clear that more advanced/complex residential buildings can withstand a lot more and more sophisticated features, however the common smart house has a small set of functions to be activated.

#### 4.1.0.1 Microphone

The microphone module that is integrated in the SSU is composed by an electret microphone embedded with a voltage comparator and an amplifying transistor.

The frequencies of the knocks were tested using a Spectrum Analyzer and confronted with the frequency range of the microphone. The spectral analysis of the knock sound showed that the predominant frequencies are in the 3Hz up to 1.5kHz interval. The frequency range of the microphone is between 20 to 10kHz so it is considered adequate. [A].

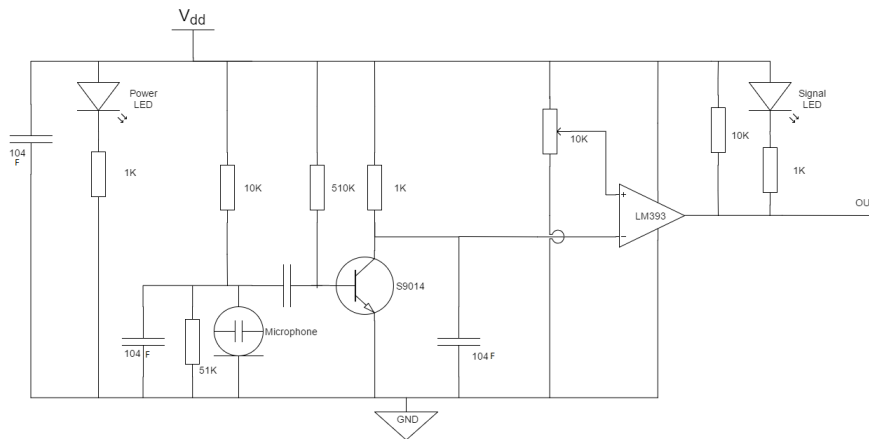


Figure 4.2: Circuit of the sound sensor module. Units: 104-0.1 $\mu$ F. (adapted [41]).

In the following figure is the main structure of the electret microphone.

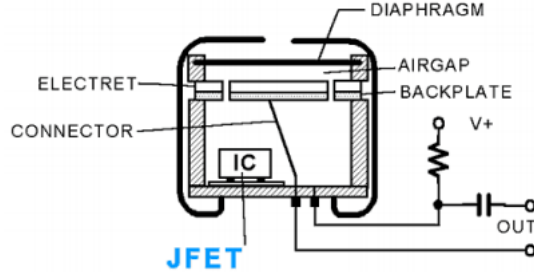


Figure 4.3: Electret Microphone (adapted [44]).

The voltage comparator allows for the detection of different levels of sound intensity through the manual adjustment of a potentiometer (variable resistor). The LM393 was implemented in this module, by comparing the voltage levels at the inverting (-), coming from the amplifier, and non-inverting (+), coming from the adjustable resistor, it will set the output port on high or low digital level [36]. A LED represents the output level, designed to turn on when the sound intensity is greater or equal than a certain level. By attaching the microphone to the wall and producing knocking sounds it is observed the level at which the potentiometer has to be in order to detect knock sounds. The calibration point is achieved through the conjugation of the number of knocks detected correctly by distance.

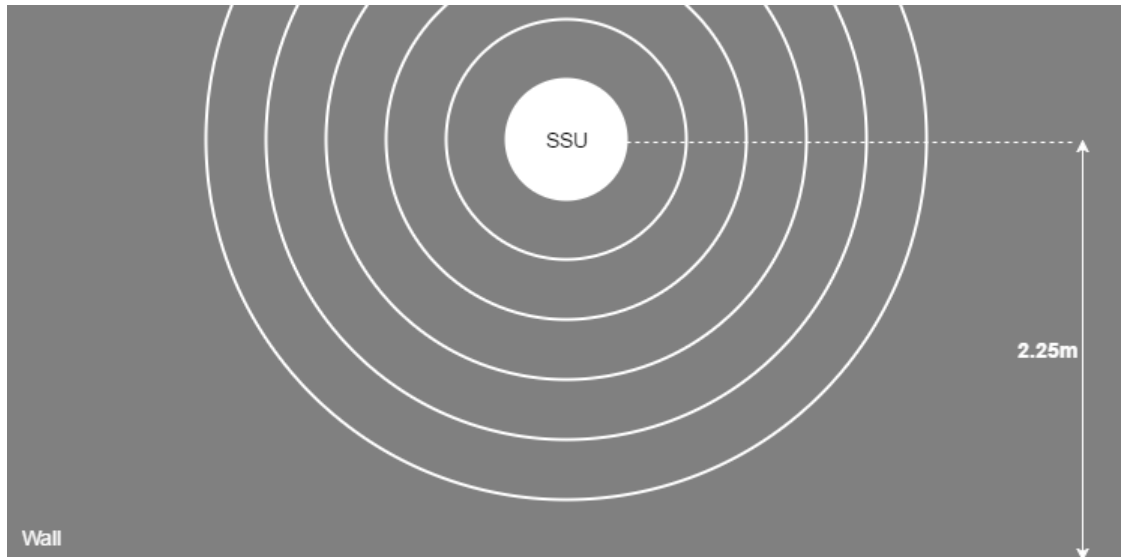


Figure 4.4: Experiment representation.

Four potentiometer positions were tested (with resistor values of approximately 0, 3.3K, 6.6K and 10K ohm), for each potentiometer position, 25 knocks were made at a distance

	Position 1			Position 2			Position 3			Position 4		
<b>Dist.(m)</b>	ID	D	ND	ID	D	ND	ID	D	ND	ID	D	ND
<b>1.00</b>	2	10	15	4	16	9	6	25	0	8	25	0
<b>1.25</b>	0	6	19	4	10	15	6	23	2	5	25	0
<b>1.50</b>	0	0	25	1	8	17	4	12	13	5	25	0
<b>1.75</b>	0	0	25	2	4	21	0	2	23	5	23	2
<b>2.00</b>	0	0	25	1	3	22	0	1	24	4	18	7

Table 4.1: Knocking Tests Experiment Result (ID - Incorrect Detection, ND - No Detection, D - Detection)

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of 1.00, 1.25, 1.50, 1.75, 2.00 meters (from the unit). The unit was tested at a distance from the ground of 2.25m, as described in the figure 36. In the experiment, there was a special care by trying to make knocks as similar as possible.

From this experiment it was found the best position in both number of detections (statistically) and quality of detection (empirically and statistically). It is observed that the best ratio of detected knocks over total knocks is the position 4, however position 3 was more accurate mainly because the high sensitivity of position 4 provoked the detection of not only knocking sounds but other environmental sounds. In 2008, it was estimated that the medium height in Portugal is 172.30 centimeters [39]. From here it is estimated that the interval on the wall where it is most probable for a user to knock on is from 75 cm (while seated on a chair) to 165cm. By applying the Smart Sensor Unit at 225 cm, pointing downwards, we get a detection range with the position 3 of the microphone with a 92 percent success on knocking detections. This allowed for detections starting from the height of 55-80 cm (from the ground up on a vertical line, aligned with the unit) to the SSU.

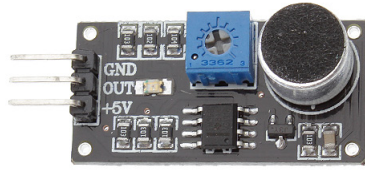


Figure 4.5: Sound detection module (adapted [41]).

#### 4.1.0.2 Piezoelectric Module

The piezoelectric disk is made of brass and it was chosen because it can both detect the amount of knocks but also the intensity. Such characteristic is of relevance because it improves the system behavior by allowing for rejection of other vibrations and knocks that do not have an intention to set this system active. The brass disk is composed by a 20mm of metal plate, 15mm ceramic plate and has only 0.2mm of thickness. The temperature interval for operation is of -20C to 70C which encapsulates the temperature interval of regular buildings. In the following figure is the schematic of the used sensor composed by a transducer, a Zener diode and a resistor. The diode is placed in order to prevent high voltages from the diode from damaging the microcontroller. It works by conducting when the 5.1V voltage is exceeded, thus deviating the electric energy from the microcontroller. The resistor objective is to bleed off any remaining charge in the transducer.

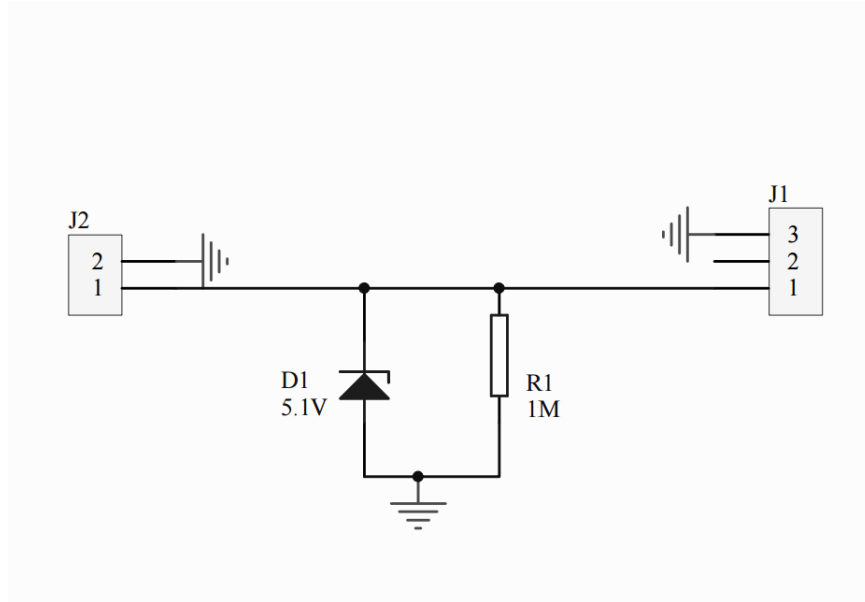


Figure 4.6: Piezo Disk Vibration Sensor Schematic (adapted [25]).

The used piezoelectric sensor has a big sensibility and uses an output that starts at 0 and goes up to 5V, which is the reference on the Arduino UNO ADC (analog-to-digital converter). After the analog to digital conversion, the values of the registers on the Arduino varied from 0 to 1023. Until the value of 200, it is programmed by software for nothing to happen. It was observed that within this interval, vibrations detected were mainly due to uninteresting events such as steps and furniture dragging. The disk in the vibration sensor module must make good contact with the surface. This increases the detection sensitivity and greatly increased the success rate of knocking detection. The piezoelectric module was attached neatly to the wall by screwing a board over the unit. The sound detection module must be pointing downwards if the module is installed in the upper zone of the wall. This installation is recommended because the top of the wall is a lot less subject to accidental touches.



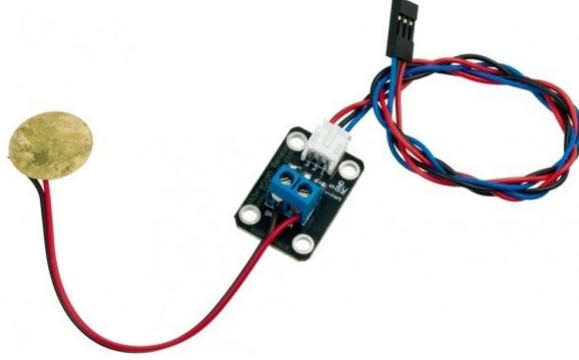


Figure 4.7: Piezo Disk Vibration Sensor Used (adapted [25]).

The following procedure is made in order to retrieve information (analogic values) that can help in the calculation of the distance between a knocking sound from the Smart Sensor Unit. Starting from 50 cm up to the implemented testing unit knocks with typically the same intensity (assured by the microphone triggering and empirical observation) knocks were made in intervals of 10 cm and the result measured on the ADC registers was reported. For each height and wall material the results shown are the average of 3 measures. The results are presented on the next table. Three types of wall are used and the value from the ADC were recorded.

<b>Height(m)</b>	<b>Brick (masonry)</b>	<b>Wood Panel</b>	<b>Plasterboard</b>
<b>1.80</b>	1010	1010	1010
<b>1.70</b>	962	1004	910
<b>1.60</b>	811	961	883
<b>1.50</b>	782	944	876
<b>1.40</b>	667	903	861
<b>1.30</b>	655	875	784
<b>1.20</b>	562	801	770
<b>1.10</b>	515	756	690
<b>1.00</b>	354	739	653
<b>0.90</b>	321	732	642
<b>0.80</b>	288	707	634
<b>0.70</b>	296	662	638
<b>0.60</b>	276	602	602
<b>0.50</b>	200	522	604

Table 4.2: Results of the vibration detections on 3 types of wall.

## 4.2 Performance

The performance measurement in this type of system was established as the latency between the user knock and the actuator and as the area coverage per sensor. This type of system does not have real time requirement, however the speed at which the system reacts is important for the user to have a pleasant experience. For this reason the overall times were object of study and were tested. The results of the tests are shown in this subsection.

### 4.2.1 Latency

Under normal circumstances the latency of this system is caused by:

- Processing time on the peripheral microprocessor.
- Processing time on the central device.
- Duration of the Connected Window.

By measuring with the `millis()` function the time between the waking of the microprocessor, until the disposal of the information to the communication module it was concluded that this item is negligible, the reading and the processing of the sensors is very fast (average of 200ms), in this system. The critic components in this part, are the consecutive readings made with the objective of improving the accuracy of the read value.

Next, the `AT+INQ` command programmed in the sketch of the central module makes the HM-10 start a scanning event in which it will scan for other bluetooth devices. The HM-10 module used in the central gateway showed an average of 2.8 seconds to complete a single scan with both peripherals advertising. These values were averaged from 10 readings of the time elapsed.



Figure 4.8: AT+INQ? command response during tests.

This latency value is the worst case scenario, the scenario where a knock is made right after a scan have been made by the central unit. The actual latency can be statistically expected to be half of that, 1.4 seconds.

The time elapsed between the knock and the activation of the relay can suffer further delays if the central gateway is connected with another peripheral. This connection window has a duration of 1 second which can be extended with further knocks on the wall. Only after the two devices (central and active SSU) disconnect there is an opening to a new scan.

To conclude the longest latency that can be experienced is 1.6 seconds plus the connected time that a central unit can be connected to another peripheral unit, which sums up to 4.6 seconds.

The situation where a peripheral unit is advertising and a connection is not made because the central unit is currently connected to another peripheral unit can be dealt with with adjustments on the timeout of the advertising. As long as the timeout of the advertising is longer than the maximum latency, there is no loss of information. However this delay will be experienced.

## 4.2.2 Sensor Unit Wall Area Coverage

For the sensor unit wall area coverage two tests were made.

The first one consisted in experimentally detect the success rates of knock detection for various wall positions and then define the covered area per sensor unit. The conditions for this test were: Sensor Sensing Unit at an height of 2.25 meters, and in a plasterboard wall.

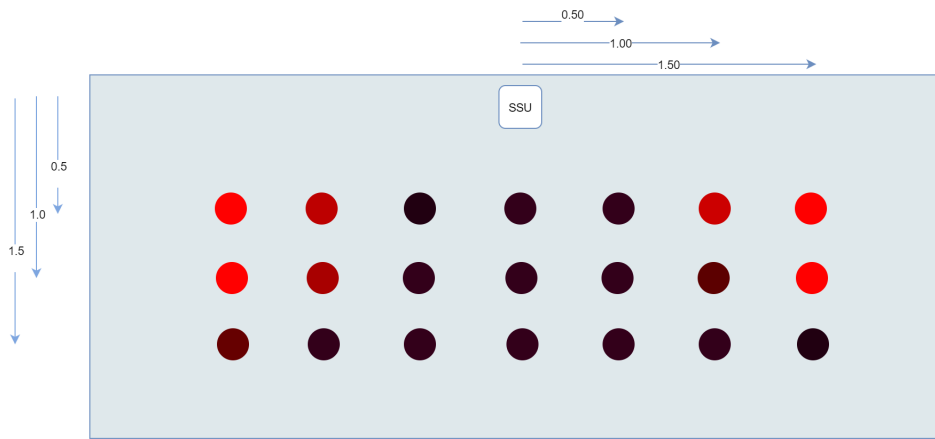


Figure 4.9: First experiment results by colour.

Sucess Knock Detection Rate Knocks per position: 25	62%	84%	92%	100%	92%	88%	64%
	80%	88%	100%	100%	96%	92%	84%
	88%	92%	96%	96%	92%	88%	84%

Table 4.3: Numeric results of the first experiment.

The second experience consisted in discovering the interaction between two units installed sequentially in the same wall and comparing the results of the two sensors to the same knocking sound.

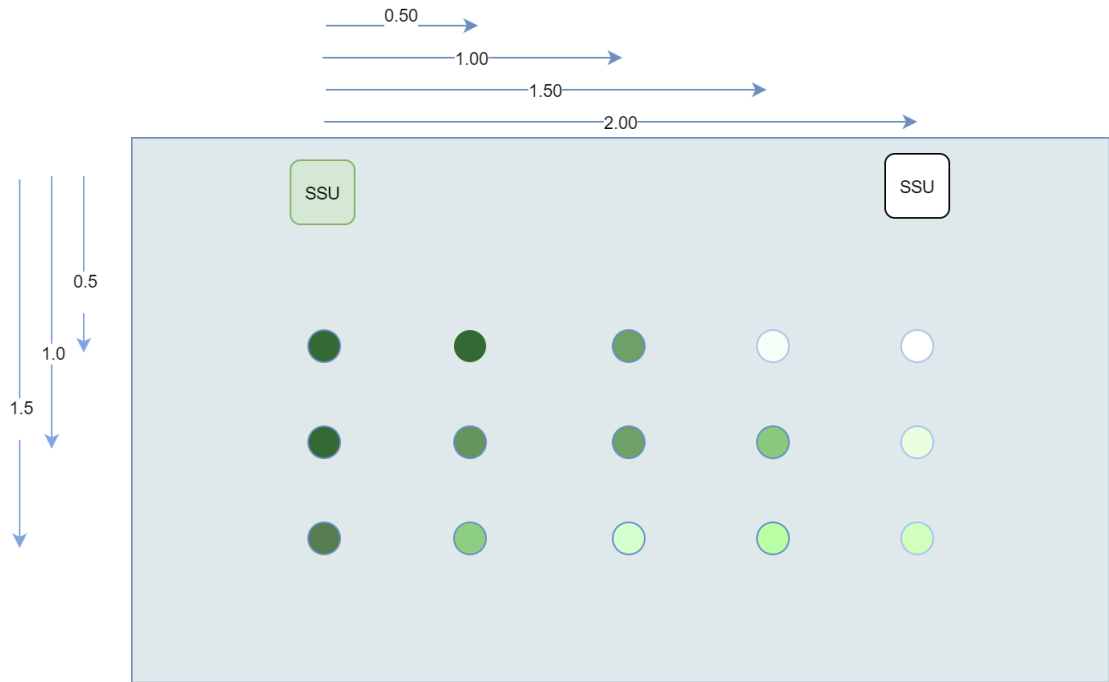


Figure 4.10: Second experiment results by colour.

	100%	92%	34%	14%	0%
Detection by SSU1left	0%	0%	30%	76%	100%
Detection by SSU2right	0%	8%	26%	10%	0%
No Detection	96%	68%	44%	20%	0%
	0%	16%	36%	72%	92%
	4%	16%	20%	8%	8%
	86%	92%	44%	60%	0%
Total Knocks made	0%	0%	40%	32%	92%
Per Position = 25	14%	8%	16%	8%	8%

Table 4.4: Numeric results of the second experiment.

From the first experiment it was clear that at a distance of 1.5 meters, horizontally, from the sensor unit, the detection rates reach critical values of 80% and at higher positions can reach percentages as low as 62%. This test allowed for the estimation of the sensor coverage area which was established to be 1 meter for each side of the sensor, which adds up to a total horizontal reach of 2 meters. The critical factor in the horizontal reach is the fact that the microphone used is directional. The main area limitation is the horizontal reach however, a slight decrease in detection accuracy is observed on lower positions. This is mainly due to attenuation of both the sound wave and the vibration by the wall materials.

The second experiment aimed to achieve an estimation of the horizontal relative position to install another unit and analyzing how the knocks would be distributed by each sensor unit. The experiment was made with two sensors separated by 2 meters, which was information retrieved from the results of the first experiment. At a 0 meter mark every knock is detected by the first unit which is expected. At 0.5 meters it is observed a small value change at 1.0 meter vertical height, with 4 knocks being detected by the second sensor unit, this is assumed as a statistically discrepancy, once both at 0.5 and 1.5 meter height, no knock was detected by the second sensor. At the 1.0 meter it was expected for the sensors to be sharing the knock detection, due to the fact that this distance is precisely the horizontal reach for each sensor. This was confirmed by the experiment. At the 1.5 meter mark, from previous results, it was expected for at least 90% of the knocks to be detected by the second unit, however that was not as evidenced, sitting at rates of 70%. This could be caused by different pressures during installation, and/or by different values of sensitivity on the sensors, mainly caused by manufacturing tolerances.

The following two figures represent the implemented units. The implementation was based on two breadboards where all the wiring and some of the electronic components were attached. Not visible in the picture is the piezoelectric module that is attached on the back of the breadboard to extra sensitivity. These units are quite bulky for a real life implementation but they can easily be made smaller by replacing the Arduino Uno's with the respective microprocessors, or with smaller versions of Arduino, design a PCB that accommodates all the electronic component and use a smaller battery.

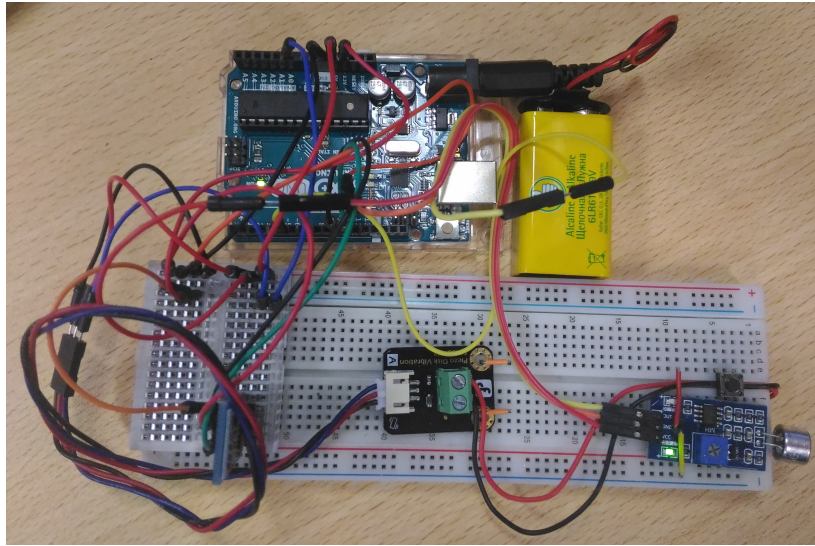


Figure 4.11: Smart Sensing Unit.

The central unit tested composed by the BLE HM-10 module, Arduino Uno, Relay Board [42], Battery and additional electronics, showed that no further connection to the relay was needed since each channel has its own active LED.

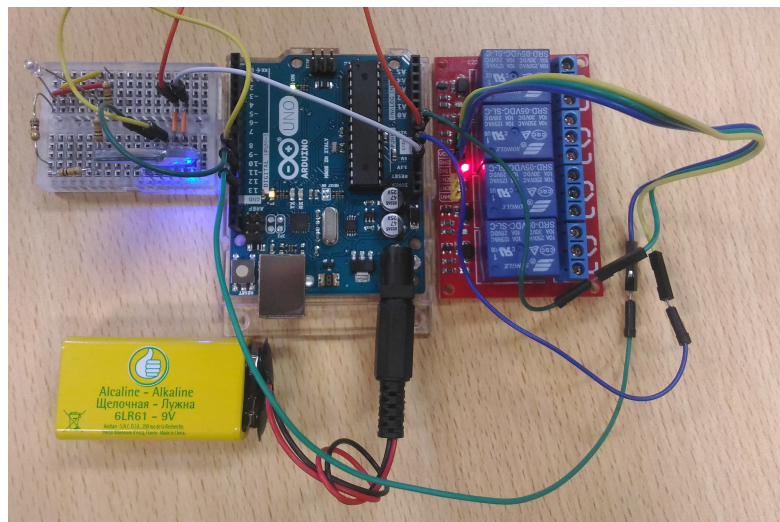


Figure 4.12: Gateway Simulator (Central).



### 4.2.3 Network of Smart Sensor Units

Tests on the implemented units showed an average covered area by sensor of 1.5 squared meters. This implies that multiple sensor sensing units must be connected to the central gateway. With this implementation, the addition of new sensors is made simple by attributing each sensor a specific name that is retrieved by a gateway. In the gateway each sensor name and respective functions to be activated must be written. Adding new units consists on this basic steps:

- programming the name on the communication module.
- replicate the part of the program that detects the name of an advertising smart sensing unit.
- switch the name for the name that was chosed.
- review the functions to be activated, by activating or deactivating certain relay ports.

Even simpler is the removal of Smart Sensing Units from the network, it is only necessary to erase the program part that detects the SSU name, on the gateway.

The network on this project consisted of 3 smart sensing units. The gateway decided which SSU to connect from the Advertising Flag Byte. After that, it reads the NAME of the higher flag and activate specific functions of that unit.

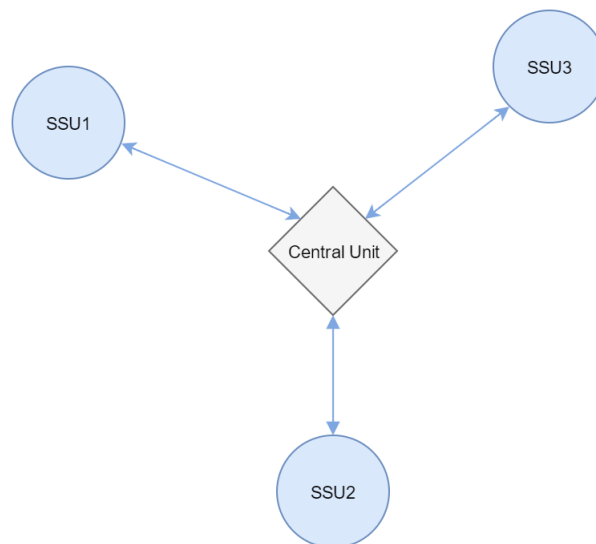


Figure 4.13: Bluetooth based Network applied in the implementation.

An alternative to the star implementation of the previous figure is the distributed imple-

mentation of the next figure. The Central Units 1, 2 and 3 are secondary Central Units and must respond to a Primary Central Unit. This distribution increases the number of hops to be made by the information however it would reduce competition to the relays. The idea behind this implementation is that at every level there is some computation of the information in order to simplify it and make the system quicker. In this implementation, there are two options:

1. All the secondary central units (SCU) are connected to the relays that activate the room functions. This option brings advantages in terms of the necessary labor to implement the system, latency and complexity. The fact that a gateway is connected to a limited number of devices, decreases the probability of collisions between interactions. The primary central unit function would be mainly collecting the data from all the secondary units and making it available for users or other systems.
2. All the secondary central units transmit the information to the primary central unit and the central unit is connected to every system that needs to be activated. This option brings the advantage of the centralization of the wiring connections in one area of the building. The secondary units in this system function would be only to process (connect and count the number of knocks and calculate the device to be activated) and forward this information in the same way with advertising packets.

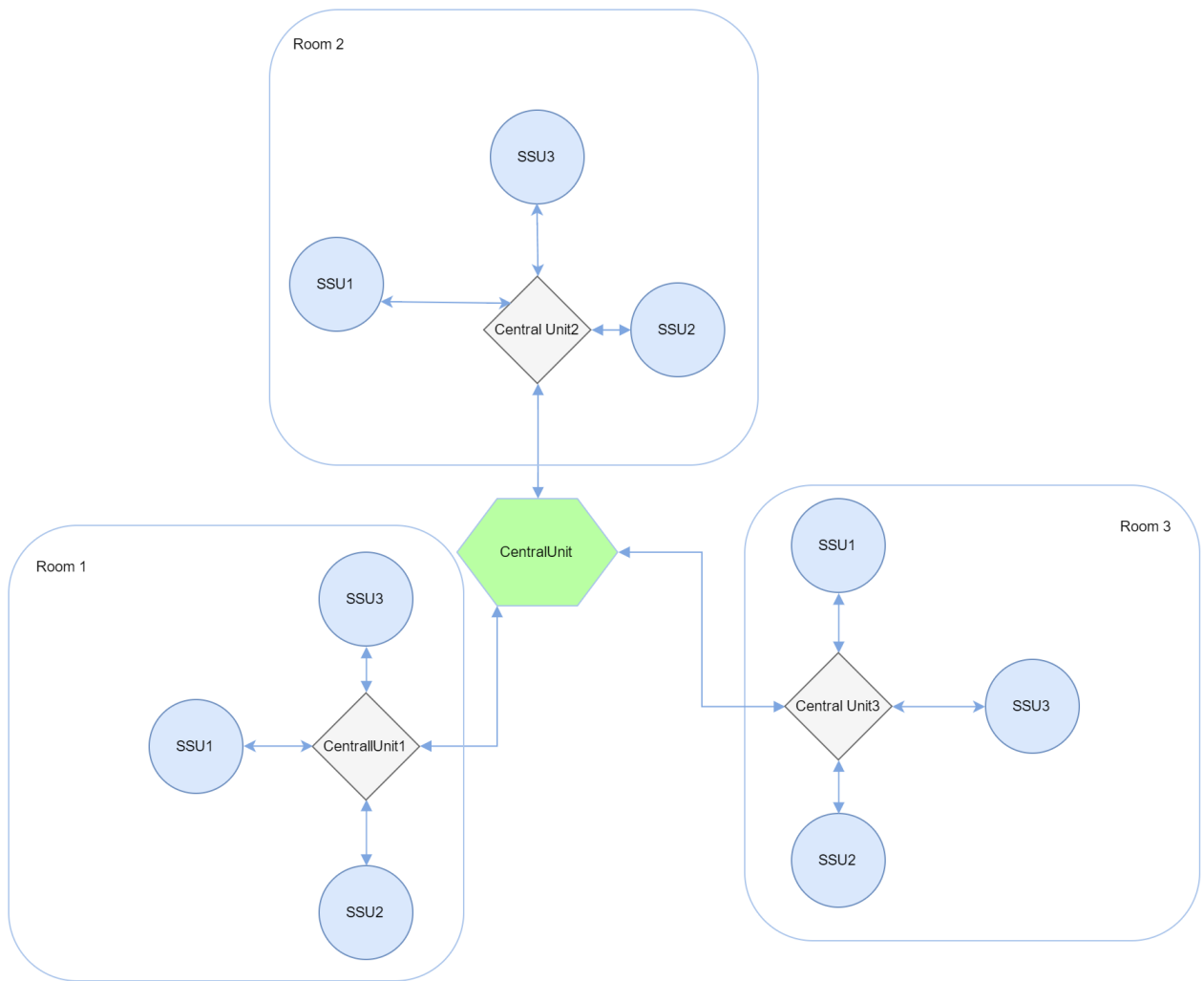


Figure 4.14: Bluetooth based Network applied to an extensive implementation.



# Chapter 5

## Conclusions

This dissertation is based on the area of domotics, and it proposes that inhabitants of a residential building can transmit commands to a central processing unit with the use of smart sensors, *i.e.* sensor that are provided with a microprocessor. The integration of the smart sensors on a network enabled for each smart sensor to have different functions, and to be detected by the central gateway with unique identification. This increases the area that can be covered in a room but also increases and simplifies the access to actuators on the house.

Primarily, this thesis started with a study on the primordial home automation technologies, such as the X10 protocol, and continually proceeded to more recent technologies, ZigBee protocol and Z-Wave systems, and finally Bluetooth Low Energy, WirelessHART and EnOcean protocols/products.

Ensuing, a smart sensing unit architecture was proposed, applying the use of Bluetooth Low Energy integrated circuits with a breakout board, the HM-10 C2541, microprocessors, the ATmega-328P embedded in an Arduino Uno board, and sensors. A similar system was produced, but this time with a Arduino Uno, a HM-10 C2541 and a relay board and was used to simulate the gateway and test the communication with the Smart Sensing Unit.

Implementation of the Smart Sensor Unit, described in the implementation chapter, showed positive results with a high rate of successful detection, mainly due to the information crossing between the two sensors. The system was subject to certain tests in the fields of performance testing and area coverage from a single unit. Both the sensors were tested and the coverage area per implemented unit is of about 1.5 to 2.25 squared meters, and this area changes with the composition of the wall. It is expected, for a regular room, to

have implemented 3 of this sensors, however this can vary with the size but also the type of compartment.

The communication between the gateway simulator and the Smart Sensing unit was achieved firstly by the advertisement characteristic of BLE 4.0 peripheral devices and then by providing a connection secure window to transmit further knocks. The implementation security was verified by the access control in the gateway, *i.e.*, only advertisements from certified addresses and with valid flags would turn into secure connection. At the same time Bluetooth Core Specification 4.0 assures that a connected state between peripherals and central devices is only achieved if the two share the same password. During the secure connection the technology Specification assures the encryption of the exchanged information.

Therefore it is concluded that Bluetooth Low Energy exhibits characteristics of an appealing technology that pushes the bounds on wireless communication mainly due to the endorsement of the leading electronic companies. This wide endorsement and investment made Bluetooth and more recently Bluetooth Low Energy into one of the most ubiquitous technologies. This ubiquitousness is the fruit of also the effort in maintaining compatibility on newer Bluetooth Low Power devices over older Bluetooth devices. This protocol was chosen for this system implementation due to the low complexity, low power, the easy addition of new Sensor Smart Units in the network and the security and reliability that are inherent to Bluetooth. At the same time this technology allows for a wide range of gateways, the residential building core doesn't have to be a fixed computer but a user's laptop, smartphone or even a tablet. The high compatibility of Bluetooth is also one of the evidences that lead to the protocol choice [37] [38]. The longer range of the Bluetooth Low Energy gives the possibility to have only one gateway per residential building which improves the structural costs of domotic installations, however it was observed during this thesis that due to the high number of interactions and actuators that exist in a building, this possibility must be the target of further work.

Regarding the energy consumption, today's processors, sensors and Bluetooth low energy communication interfaces show very low energy requirements. At the same time, the "Smartphone Era" induced advancements in battery technology, which made possible for these units to be implemented at very low maintenance cost per unit and lasting for over a year with a single coin sized battery.

## 5.1 Critic Analysis

The proposed idea is a big change in the way we communicate with a building. With every new idea, new problems and challenges emerge, the introduced idea is not different, there are a problems and difficulties that can't be overlooked. This section focus on the discussion of the most important downsides that such a device showed and presents whenever possible alternatives and ideas to overcome them.

### 5.1.1 Knock Filtering

One of the obvious improvements for this system would be the use of acoustic recognition. Comparing the detected sound with a previous knocking sound and comparing each one frequency spectrum can improve the system efficiency. This kind of addition however can increase greatly the cost of the system. Fortunately, due to the limited number of sounds and vibration made on a wall this additional complexity can be avoided.

### 5.1.2 Knock Positioning

With such system implemented throughout a house, multiple devices must be spread around the house. Every device is programmed in a way that it detects knocking sounds. Even though the sensitivity of each sensor can be empirically adjusted to only sense a certain area, this area can change with environmental factors such as humidity, temperature, presence of furniture between other factors.

To further improve this downside, a type of synchronization can be implemented. The presence of a real time clock in each sensor, with the additional sharing of the time values within a certain interval of time, with both neighbor sensor units and central units creates a mesh network that can make the system virtually free of error. If each sensor unit could detect precisely when a knock was detected by his sensors, the central processing unit can easily know which of the walls was knocked on. The cost of such precise real time clocks and their implementation would however turn this project impractical.

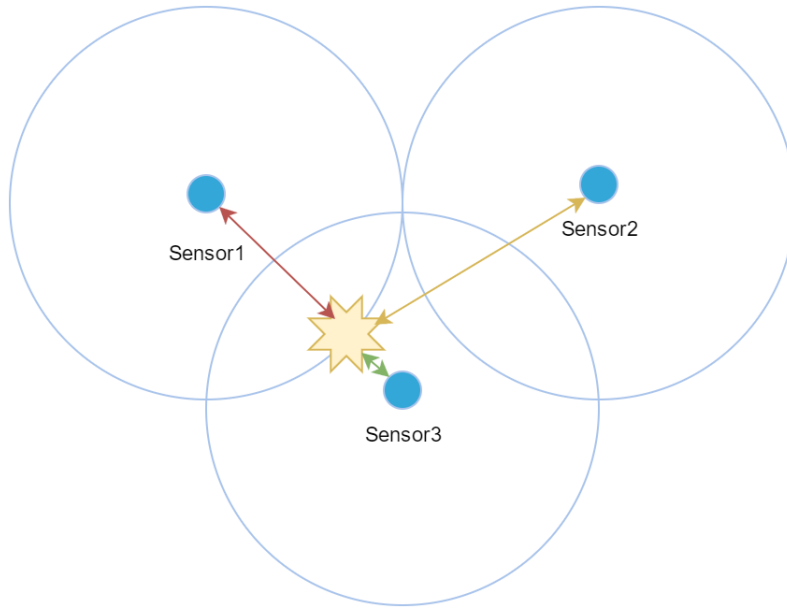


Figure 5.1: Distance from knock to each sensor, example of triangulation.

It is obvious that intensity of the a sound is highly correlated with the distance it was made, especially in a controlled environment such as a room inside a house. The price of the analogic sensors of this application are in the same range of digital sensors and this characteristic is a alternative to improve the system functionality without adding substantial costs.

### 5.1.3 Knocking Combinations, Codes and Alternative Gestures

It is a reality today, there are multiple electronic devices present in a single room. Each electronic device has its own functions that can be addressed by the unit. This presents a challenge, how to make use of a system to access multiple electric devices and their specific functions. The way approached to address this problem is considering a time window where the number of knocks and the time between consecutive knocks are taken into consideration.

With this kind of approach, a sensor unit will be sensing during a time window and then processes the information that was gathered, deciding what electric device and what type of function of the specific device is to be enabled. The addition of different types of gestures, for example, swiping could be added and be rearranged with sound recognition hardware and software.



## 5.2 Future Work

In this section is made a presentation of different paths that can further develop the idea presented in this thesis. This ideas are the outcome of the analysis on older and recent technologies and the implementation and testing of the system.

In future work, efforts can be done in order to integrate the smartphone into this sensing, providing access to all available functions at the gateway. Information from the gateway, such as light state, window blind state, generally state of individual actuators and also readings from certain sensors might be directly shared with the user. Since the network is based on Bluetooth, this values can be shared directly with smartphones, tablets or any other electronic device that possess a Bluetooth connectivity and from this point to the Internet to be accessible anywhere in the world. In the sensing unit, the integration of other types of sensors and more sensors in different spacial positions can show positive effects on the detection accuracy. Further studies on sounds that are made inside residential buildings and their frequency bands can help improve the accuracy of the detection by providing a degree of filtering. The speed of communication can be made quicker, with newer recent versions of bluetooth modules.



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# Appendices

# Appendix A

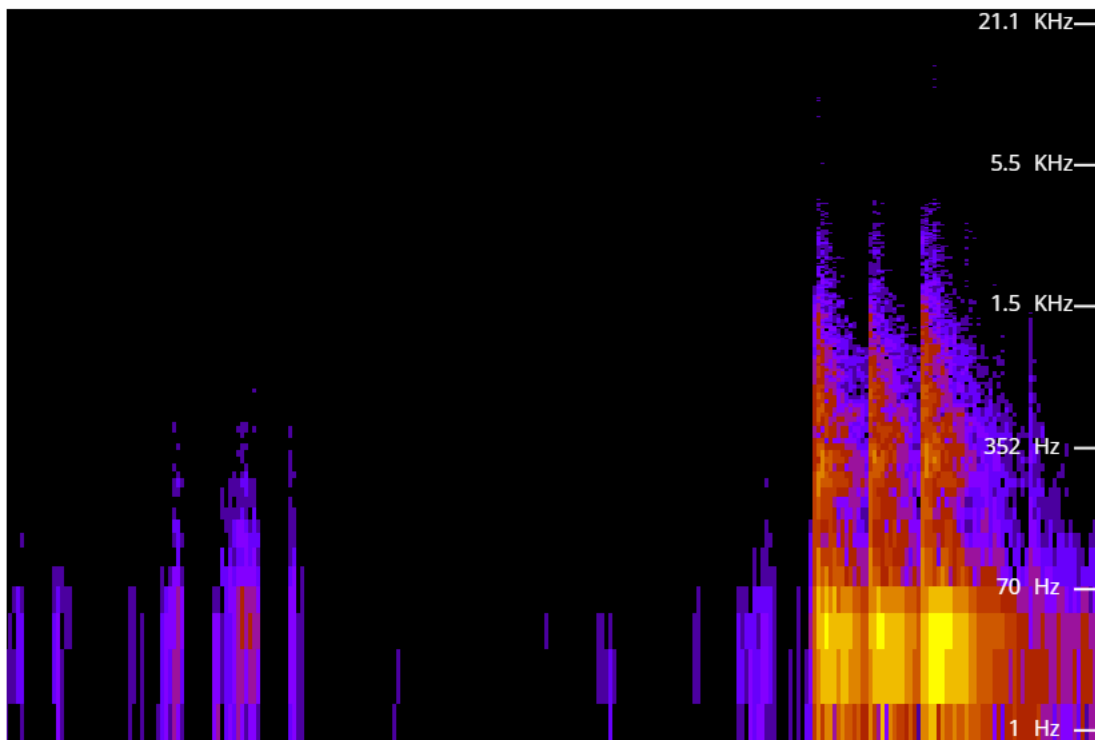


Figure A.1: Knock frequency analysis (Spectrum Analyzer, academo.org).